The Introduction of a Sound Quality Engineering Process to Jaguar Cars

Gerard T. Dunne, BEng, MSc.

EngD Executive Summary

The University of Warwick

School of Engineering

Warwick Manufacturing Group

June 2003

Abstract

The control of the noise and vibration generated by an automobile is referred to as Noise, Vibration and Harshness (NVH) engineering. It involves identifying the design detail required to reduce the noise and vibration inside the passenger compartment of the vehicle to levels that are acceptable to the customer. It also involves delivering an engine or a powertrain sound character that is both pleasing to the customer and that suits the character of the vehicle. Tuning the sound generated by a vehicle to deliver a particular character is referred to as Sound Quality Engineering. This document summarizes the work of the EngD research programme that was aimed at developing a structured process for engineering the Powertrain Sound Quality of an automobile.

The need for developing a Sound Quality Engineering Process at Jaguar Cars was identified through a review of customer evaluations of the sound in Jaguar's vehicles and those of its competitors. This review established that Jaguar's existing vehicles were trailing the leading competition in terms of the delivery of Powertrain Sound Quality. The reason for this shortfall was that the NVH Department at Jaguar did not have a focus on delivering the customer requirements. Without this focus there was no means of using the customer level requirements for Sound Quality to drive the vehicle design process. The EngD research programme resulted in the formulation and implementation of a Sound Quality Engineering Process at Jaguar Cars that addressed this need.

The first part of the research programme involved developing a means of quantifying the differences in the subjective Sound Quality character perceived by the customer. It was established that the subjective nature of the Powertrain Sound Quality could be represented by two underlying dimensions; a measure of the degree of Refinement and a measure of degree of Powerfulness. An assessment technique was developed that enabled the subjective Sound Quality character for a given vehicle to be quantified through its location within a 2-Dimensional Sound Quality Space, the axes of which were defined by each of the two underlying dimensions of Sound Quality. This 2-Dimensional Sound Quality Space provided the means of quantifying the differences in the Sound Quality characters for all of the vehicles competing in the luxury vehicle sectors. It was applied to define subjective Sound Quality targets for all of the new vehicle programmes at Jaguar Cars. These targets identified the required improvements to each of the two underlying dimensions of Sound Quality needed to address the shortfalls in Jaguar Cars' existing vehicles.

The second part of the research programme involved identifying the key acoustic features within the sound signatures of Jaguar's vehicles that were responsible for determining the differences in subjective perception between these vehicles and their competitors. The changes to these key acoustic features were related to the required improvements to each of the two dimensions of Sound Quality that were established from the subjective target setting process.

The final part of the research programme involved developing techniques that linked these key acoustic features to the noise sources and paths that were responsible for generating them. Through this link it was possible to establish the changes to these noise sources and paths that were necessary to deliver the required changes to the key acoustic features. In this way the required improvements to each of the two underlying dimensions of Sound Quality were used to define the vehicle design specification at the concept stage of the vehicle development programme and consequently drive the vehicle design process. The ability to link the subjective customer level requirements for Sound Quality to the design detail specification has overcome the previously identified shortfall within the NVH development process at Jaguar Cars.

The techniques developed during the EngD research programme were formulated into a Sound Quality Engineering Process. Although the process was developed for Jaguar Cars the findings from the research and the techniques developed have since been applied by the different brands within the Ford Motor Company. Within Jaguar Cars the process has been implemented across all of the new vehicle programmes. It has directly resulted in significantly improved Sound Quality characters in the new vehicles that have been recently introduced to the luxury vehicle market.

Acknowledgement

I would like to thank a number of people for the help and support that they have given me throughout the EngD programme.

First of all I would like to thank the NVH management team at Jaguar Cars for providing me with the opportunity to conduct the research programme. Without their support and their willingness to allow me to divert part of my working time to conduct the research it would not have been possible to complete the programme. In particular I would like to thank Mr. Andrew Wheeler, Mr. Roger Staines and Mr. Dieter Schwarz.

I would like to thank Dr. Paul Jennings of Warwick University for his support and his guidance throughout the programme. I would also like to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, who provided the grant to conduct the research.

Finally I would like to thank my wife Maureen, and my son Kaelan, for their support and in particular for their acceptance of the disruption that the programme has brought to our lives. Now that I have completed we can all begin to spend our weekends together as a family.

Declaration

I confirm that the work contained in this document is my own unless otherwise stated

Gerard Dunne, 20th June 2003.

Contents

List of Figures

List of Tables

1. Introduction

This document summarises the work of the EngD research programme into Sound Quality Engineering. The purpose of the research programme was to develop a process for introducing a structured approach to Sound Quality Engineering that could be incorporated within the existing vehicle development process at Jaguar Cars. This document summarises the techniques developed during the EngD research programme that were aimed at introducing this Sound Quality Engineering Process to Jaguar Cars.

Noise Vibration and Harshness (NVH) is the acronym used within the automotive industry to describe the engineering development to control the noise and vibration produced by the vehicle. The term Sound Quality has been used to cover all aspects of vehicle noise or sound. These aspects include both the exterior and the interior sounds produced by the vehicle. The total vehicle sound can be classified according to the sources of the sounds. These are the sounds generated by the engine or the powertrain, the sounds generated by the interaction of the vehicle wheels with the road surface, the sounds generated by the air rushing over the vehicle outer surface, and the sounds generated by the various motors and mechanisms inside the vehicle cabin. These sound sources are referred to as Powertrain NVH, Road NVH, Wind Noise, and Craftsmanship NVH respectively. Sound Quality Engineering can refer to the development of the vehicle to address each of these sound sources. However, rather than covering all aspects of vehicle Sound Quality the focus of the EngD research programme has been on the Powertrain aspects of Sound Quality inside the vehicle passenger compartment.

Chapter 2 reviews the background to the subject. It defines Sound Quality Engineering as the implementation of a disciplined approach that can be used to identify the design detail required to deliver a distinctive subjective sound character. The importance of Sound Quality is explained by demonstrating how different degrees of achievement in NVH performance have resulted in different levels of customer satisfaction within the luxury vehicle sector. It is shown that the delivery of increased levels of customer satisfaction is not achieved merely by reducing the interior noise levels but is rather achieved by delivering a Sound Quality performance tuned to match the character of the vehicle.

The need for the development of a Sound Quality Engineering Process is illustrated by outlining the status of the NVH and Sound Quality development at Jaguar at the start of the research programme. Chapter 3 explains that Jaguar's existing products were trailing the leading competitors in terms of both the NVH and Sound Quality performance. The first reason for this was that Jaguar did not have a robust target setting process that linked the customer level requirements for NVH to the vehicle design detail necessary to deliver these requirements. The second reason was that the focus of the NVH activities at Jaguar had been purely on the noise levels and not the Sound Quality character. Without this focus there was no means of incorporating the delivery of Sound Quality within the vehicle development process. The lack of a focus on Sound Quality had resulted in Jaguar's products failing to support the brand's core-mark value of Refined Power.

The status of Sound Quality Engineering at Jaguar and the need to address the shortfalls in the delivery of Sound Quality within Jaguar's products were used to outline the aim of the research. This was to develop the tools and techniques to enable a Sound Quality Engineering Process to be introduced to Jaguar Cars. This aim resulted in the formulation of a set of objectives for the EngD research programme. These objectives were initially developed by the author and then agreed to by the NVH management team at Jaguar. They are detailed in Chapter 4. Throughout the duration of the research programme all of the work involved in developing the elements of the Sound Quality Engineering Process was undertaken by the author, but under the guidance of the NVH management team at Jaguar. This ensured that the process developed met the requirements of each of the vehicle programme teams.

Prior to initiating the research a review of the previous published literature on Powertrain Sound Quality was conducted. Chapter 5 summarises the key findings from this literature review. The review identified two clusters of previous work that were to be significant in terms of the research objectives. The first was the group of papers that focussed on the quantification of the subjective nature of Sound Quality in terms of a number of key factors or underlying dimensions. The second was the group of papers that focussed on the identification of the acoustic features that were responsible for generating different subjective characters. The findings identified from the review of the previously published literature were used to guide the development of the Sound Quality Engineering Process.

Chapter 6 outlines the research that was conducted to develop the Sound Quality Engineering Process. It outlines the methodology used and the individual work packages that were formulated to address each of the six research objectives. The starting point was the formulation of a concept Sound Quality Engineering Process. The research work was then structured to deliver each step in this concept process. In order to ensure that the process could be incorporated within the vehicle development process it was necessary to select a new vehicle programme at Jaguar in which each of the steps of the new concept process could be developed and validated. The timing of the X350 vehicle programme, the replacement for the existing XJ8 vehicle, aligned with the expected timing of the EngD research programme and consequently it was selected as the pilot application programme to validate the techniques developed to deliver each step in the process.

The remainder of Chapter 6 outlines the research work packages that were developed to deliver each step in the Sound Quality Engineering Process. The first step in the process was referred to as *Understanding the Requirements of the Sounds* and was focussed on establishing the state of the competition and the existing Jaguar product range in terms of the subjective differences in Sound Quality perceived by the customer. It involved a review of market research data and internal vehicle appraisal data. It also involved conducting a series of jury listening studies that identified the subjective differences in Sound Quality expressed in terms of a series of semantic descriptors. The findings from these reviews were combined to develop a process for measuring and quantifying Sound Quality. This process characterised the nature of Sound Quality according to a number of underlying dimensions. This characterisation was then used to set subjective Sound Quality targets for new vehicle programmes.

The next section in Chapter 6 outlines the work packages that were conducted to deliver the second step in the Sound Quality Engineering Process. This step was referred to as *Understanding the Sounds.* It involved identifying the key acoustic features within the sound signatures of different vehicles that were responsible for the differences in subjective perception between them. This work involved applying the findings established from the review of the previous literature to compare the Sound Quality characters of the Jaguar XJ8 and its competitors. This was followed by a series of further studies that identified the key acoustic features that were responsible for the different subjective characters and established the effect of modifications to these key acoustic features on the subjective perception. The techniques used to identify the key acoustic features on the XJ8 vehicle and its competitors were formulated into the elements required to deliver the second step in the Sound Quality Engineering Process.

The last section in Chapter 6 outlines the work packages that were conducted to deliver the third step in the Sound Quality Engineering Process. This step was referred to as *Understanding the Vehicle.* It involved identifying the design detail responsible for generating the key acoustic features, and then establishing how predicted modifications to this design detail could be used to set Sound Quality target sounds. A process was developed that linked these target sounds to the changes in the design detail required to deliver the targets. This was a key outcome from the EngD research programme as it provided the means of using the Sound Quality Engineering Process to drive the vehicle development process.

The steps of the Sound Quality Engineering Process were initially developed and applied on the X350 vehicle programme. The application and validation of the process on this vehicle programme resulted in the final version of the Sound Quality Engineering Process. The elements of each step in this final version are outlined in Chapter 7. Chapter 8 provides a brief review of the subsequent implementation of the process on all of the new vehicle programmes at Jaguar that followed the X350 vehicle programme. The implementation of the process on each of these vehicle programmes was undertaken jointly by the author and other members of the NVH Department at Jaguar. In this way it was possible to ensure that the knowledge and techniques developed within the research programme could be transferred throughout the NVH Department. Chapter 9 reviews the principal findings of the EngD research programme. It identifies the key learning points established from the research and reviews the key strengths of the Sound Quality Engineering Process. It also identifies the weaknesses associated with the process and recommends a number of areas for further research. Finally Chapter 10 provides a route-map through the EngD portfolio, outlining the work packages that are detailed in each of the submissions and the order in which they need to be read.

2. The Definition and Importance of Sound Quality Engineering

2.1 What is Sound Quality Engineering?

The concise version of the Oxford English Dictionary [1] defines Sound Quality as "The distinctive character of a sound, other than its pitch or loudness". This definition of Sound Quality can readily be applied to the Noise, Vibration and Harshness (NVH) development activities within the automotive industry. Typically much of the work reported by the NVH Departments within the industry is in the form of 2-Dimensional plots, with the x-axis representing the frequency content of the sound, and the y-axis representing the amplitude of the sound. This means of illustrating sounds is displayed for two different sound recordings in Figure 1.

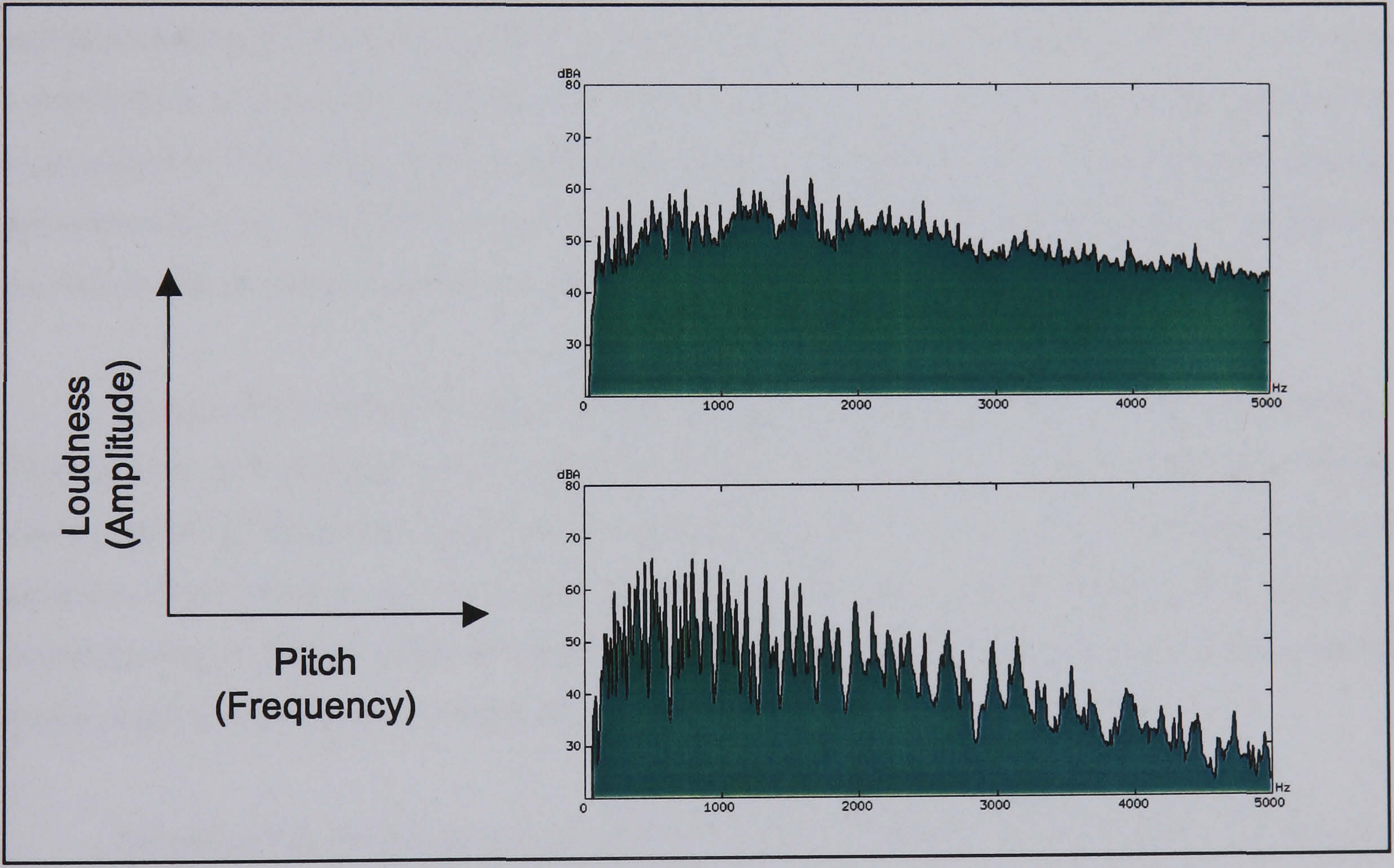


Figure 1: Pitch and Loudness representation of Sound

Each of the traces illustrated represents a sound recording made inside a passenger vehicle. It is possible to make a number of conclusions about these sounds from these 2-Dimensional representations. The upper sound, for example, has higher levels within the higher frequency region, whilst the lower sound is more harmonic in nature, and is dominated by a smaller number of tones of high amplitude. There are other analyses that can be applied to these traces that can be used to identify the differences between them, but these simple representations of the sounds in terms of their frequency (pitch) or amplitude (loudness) will never convey the true nature of these sounds. In fact, rather than representing vehicle sounds such as engine or road noise, the traces illustrated in Figure 1 are actually recordings of two types of music played through the in-car entertainment system, the upper trace representing a recording from the rock band Aerosmith, the lower trace an orchestral piece from Elgar. It must be concluded therefore that there are features or distinctive qualities in the sounds, other than their pitch or loudness, that define the way they are perceived. The introduction of an alternative approach to NVH characterisation that captures these *distinctive qualities* is therefore the first key element of Sound Quality Engineering.

Sound Quality is a discipline that falls within the field of psychoacoustics. Psychoacoustics is the science of sound perception, and involves the study of both the physiological and the psychological aspects of sound. In the most widely recognised comprehensive review of psychoacoustics, Zwicker [2] comments that our *subjective reaction* towards sounds is based upon a combination of a number of factors. The most important of these include our experience and our expectations of the sounds, and our own personal tastes and preferences. This *subjective reaction* determines how we interpret the sounds and whether or not we find them pleasing. Our *subjective reaction* to the sounds is therefore the second key element of Sound Quality Engineering.

Engineering involves the manipulation of physical quantities to achieve a desired outcome. Therefore the third and final element of Sound Quality *Engineering* involves identifying the *design detail* required to deliver the distinctive qualities of the sound. The link between the psychological aspects of Sound Quality and the vehicle development process is one that transfers the science of Sound Quality to the discipline of Sound Quality Engineering. The identification of the required *design detail* is the step that provides engineering value.

Sound Quality Engineering is therefore essentially composed of three elements. It involves developing a disciplined approach that can be used to identify the *design detail* required to deliver the *distinctive qualities* needed to achieve the desired *subjective reaction* to the Sound Quality character of a vehicle. The identification of the requirements for each of these elements and linking them together in the form of a Sound Quality Engineering Process has been the focus of the EngD research work.

2.2 The Importance of Sound Quality Engineering

A vehicle's Sound Quality, like its handling or steering characteristics, is a key vehicle level attribute. It is important for the delivery of customer satisfaction for a number of reasons. The first and most important of these relates to its ability to convey product quality. The delivery of Sound Quality helps to enhance the impression of the overall quality of the product. It serves to illustrate the thoughtfulness of the design and the quality of execution and it provides confidence that the vehicle is functioning properly.

The ability of Sound Quality to satisfy the customer requirements can be best demonstrated through the Kano Model of Quality [3] illustrated in Figure 2. This model identifies three types of quality; Basic Quality, Spoken Performance and Excitement Quality, and relates the degree of achievement of each type to the level of customer satisfaction achieved.

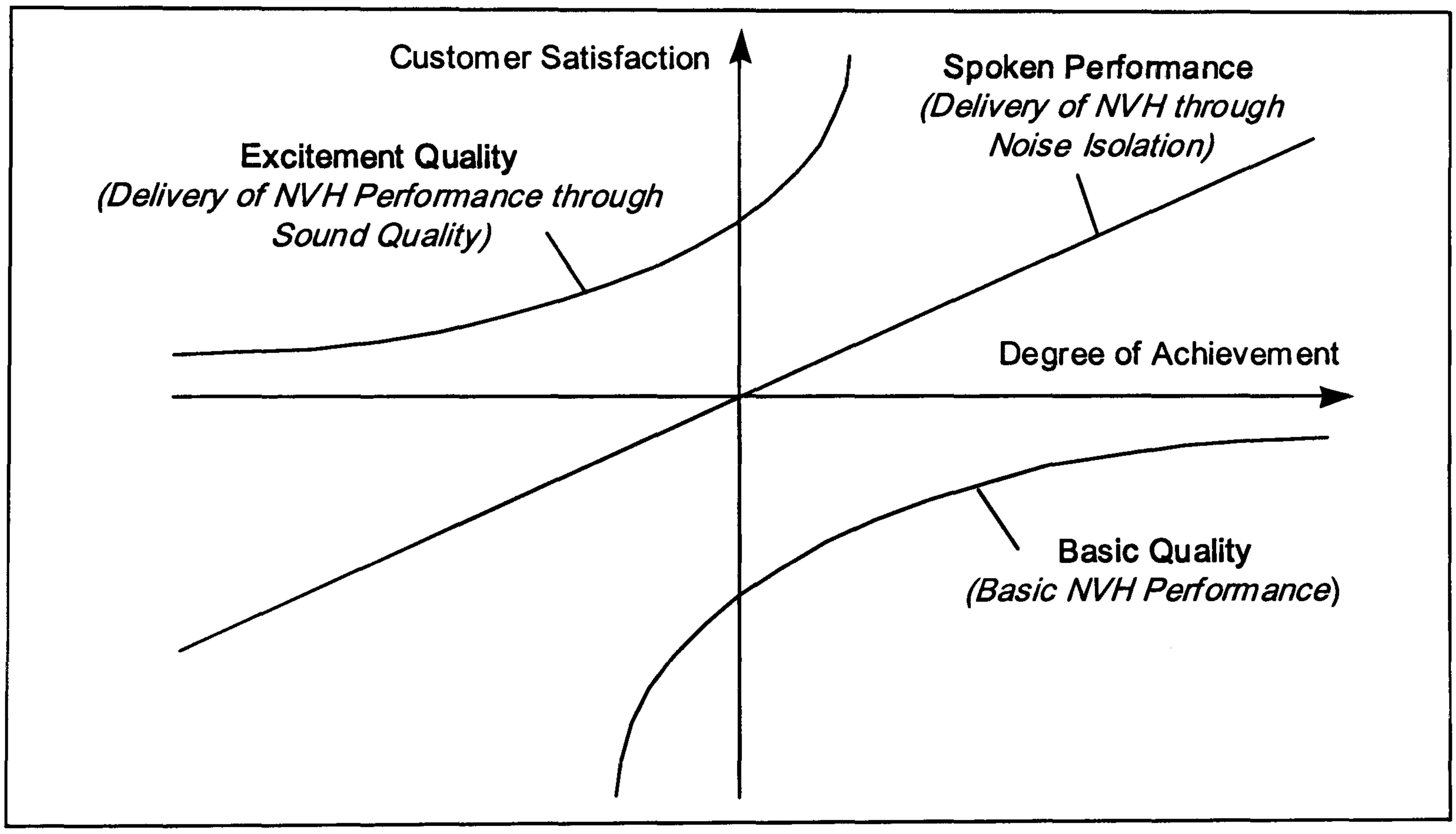


Figure 2: Kano Model of Quality

The Kano Model of Quality may be readily applied to the delivery of NVH and Sound Quality. The basic level of NVH performance falls into the Basic Quality category. Without achieving a certain level of noise and vibration isolation that is expected by the customer, the levels of customer satisfaction rapidly falls away. However beyond the delivery of certain level of performance the degree of customer satisfaction does not increase. Any vehicle competing in the luxury vehicle sector needs to demonstrate the delivery of a basic level of NVH performance in order to compete in the marketplace.

Beyond the delivery of the basic level of NVH performance however, the author argues that Spoken Performance Quality and Excitement Quality are two types of quality that can be delivered through NVH and Sound Quality. This can be illustrated in Figure 3, which displays the location of different vehicles competing in the premium luxury vehicle sector within the Kano Model. The x-axis represents the peak loudness, plotted in reverse to fit the model, measured in each of the vehicles undergoing a 2nd Gear Wide Open Throttle (2GWOT) Acceleration. The y-axis represents the level of customer satisfaction, expressed on a 1-10 scale, derived through a market research survey that requested customers of these vehicles to rate the sound of the engine while accelerating. The detail of this market research study is included in the submission to the EngD portfolio titled *Subjective Sound Quality Target Setting* [4].

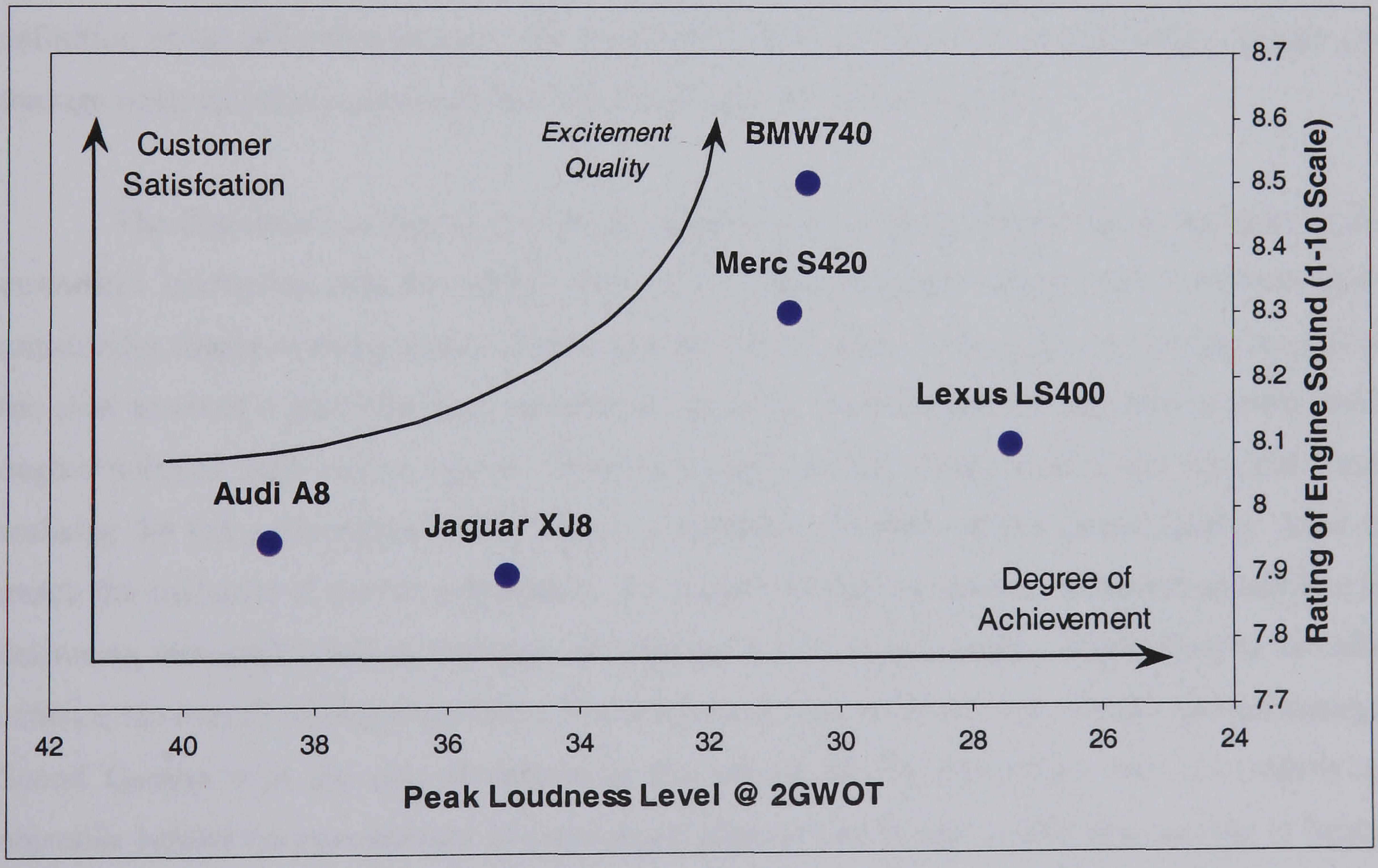


Figure 3: Customer Satisfaction vs. Degree of Achievement in Vehicle NVH Performance

The delivery of high levels of customer satisfaction through high levels of noise isolation has been best illustrated by the Lexus LS400 vehicle. Of all of the vehicles measured this vehicle exhibited the highest levels of noise isolation, as demonstrated by the lowest peak loudness level.

The author argues that the Lexus LS400 vehicle is delivering customer satisfaction in the form of Spoken Performance Quality. The high levels of noise isolation have directly resulted in increased levels of customer satisfaction. However, despite the higher loudness levels in each of the BMW740 and the Mercedes S420 vehicles, both of these vehicles were rated by the customers to have higher satisfaction levels than the Lexus LS400. The author argues that the reason for this higher level of customer satisfaction is as a result of the Sound Quality of these vehicles. They are delivering high levels of customer satisfaction through Sound Quality rather than through noise isolation. These increased levels of customer satisfaction through the delivery of Sound Quality imply that within the model illustrated in Figure 3, Sound Quality can be regarded as a form of Excitement Quality.

Using the Kano Model of Quality it can be seen that increased levels of customer satisfaction for the Jaguar XJ8 can be achieved through the delivery of Excitement Quality. It is argued that this can be achieved through the delivery of Sound Quality rather than through noise isolation. Through the use of the Kano Model therefore it has been possible to provide a clear definition of the difference between the delivery of NVH performance through Sound Quality and through noise isolation, expressed in terms of customer satisfaction levels.

The importance of Sound Quality can also be seen in the influence that it can have on the customer's interaction with the vehicle. Hutchins [5] has provided evidence that customers drive unnaturally simply to avoid adverse Sound Quality effects, like changing gear or driving too fast or too slow to avoid a particular noisy driving speed, or by altering their driving style to avoid harsh engine noise at high engine speeds. These unnatural driving styles prevent the customer from realising the full performance of the vehicle. Conversely a vehicle with a Sound Quality tuned to match the character of the car can enhance the overall driving experience. Therefore in addition to delivering increased levels of customer satisfaction in NVH performance, Sound Quality can also enhance the overall driving experience. The delivery of high levels of customer satisfaction through Sound Quality with the aim of enhancing the overall driving experience was the underlying objective behind the development of a structured approach to Sound Quality Engineering at Jaguar Cars.

3. The Status of NVH and Sound Quality at Jaguar Prior to the EngD

'Sound Quality' is a key phrase that has been used throughout the automotive industry since the early 1990's to capture the fact that NVH performance is not only about the delivery of refinement through a reduction in the noise and vibration levels, but is also about the delivery a specific sound tuned to match the character of the vehicle. For Jaguar, the delivery of high levels of refinement in its vehicles has always been a priority. This has been captured in the Jaguar core-mark value of 'Refined Power'. This core-mark value is essentially defined as the smooth delivery of power from responsive powertrains. It also involves delivering a Powertrain Sound Quality tuned to match the character of the car. The customer level NVH requirement is to minimize the levels of noise and vibration at idle, under light load drive-away and when cruising, and to generate a brand-enhancing positive Sound Quality feedback during performance driving. To use the feline phrases associated with the Jaguar name, the requirement is to *purr* at idle and to *growl* when accelerating.

However, despite this rhetoric there was a growing body of evidence that indicated that far from excelling in the delivery of Powertrain Refinement, Jaguar's products were beginning to significantly trail the leading competition. This has been indicated in the application of Kano Model of Quality illustrated in Figure 3, where the degree of achievement in NVH performance has been compared with the levels of customer satisfaction for the Jaguar XJ8 vehicle and its competitors. These results are based upon a much more detailed analysis of the levels of customer satisfaction with the NVH performance of Jaguar' s vehicles. This analysis, detailed in the submission to the EngD portfolio titled *Subjective Sound Quality Target Setting* [5], indicated that the levels of customer satisfaction with the NVH performance of Jaguar's vehicles was significantly trailing the leading competition. In particular, for the XJ8 vehicle, the levels of refinement or noise isolation were trailing the levels of the Lexus LS400 vehicle, and the Sound Quality character was trailing the class-leading BMW740. There was significant evidence therefore that rather than supporting the core-mark value of Refined Power, Jaguar's products were failing in its delivery.

The reason why Jaguar's products were failing to deliver the brand's core-mark value of Refined Power was that Jaguar did not have a process that linked the customer level requirements for NVH and Sound Quality to the vehicle development process. The existing target setting process was simply based upon benchmarking the noise levels of the leading competition and futuring these benchmarked levels to identify a target level for a new vehicle programme. These target levels, however, were not used to drive the vehicle development process. The vehicles were developed with these targets in mind but there was no link between them and the specific design detail required to achieve them. In effect therefore, the lack of a robust target setting process that linked the customer requirements to the vehicle hardware specification was the principal reason why Jaguar's products were failing to match the levels of customer satisfaction in NVH performance achieved by its competitors.

The other reason why Jaguar's products were failing in the delivery of Refined Power was that there was no *real* focus on the Sound Quality requirements. The focus had been purely on the absolute noise levels. There had not been any focus on the subjective differences in the sound character between Jaguar's vehicles and those of its competitors, nor had there been any focus on the reasons for these subjective differences. Within the Product Development Organisation at Jaguar Sound Quality had been referred to as a key vehicle level requirement, as it had been throughout the automotive industry, but there was no means of incorporating the delivery of Sound Quality within the vehicle development process. Without designing for Sound Quality it was not surprising that Jaguar's products were trailing the competition in the delivery of Sound Quality.

In summary therefore, prior to initiating the EngD research project into Sound Quality, there was evidence that Jaguar's products were beginning to significantly trail the competition in terms of the delivery of refinement. This had resulted in Jaguar's products failing to deliver the brand's core-mark value of Refined Power, and consequently failing to support and enhance the Jaguar brand image. The principal reasons for this were that Jaguar did not have a process that linked the customer level requirements for NVH and Sound Quality to the vehicle design specification, and had no means of incorporating the delivery of Sound Quality within the vehicle development process. In order to address these shortfalls it was proposed to develop a Sound Quality Engineering Process that linked the delivery of the Jaguar core-mark value of Refined Power to the customer level requirements, and to incorporate this process within the overall vehicle development process. This would enable the subjective customer level requirements for NVH and Sound Quality to drive the vehicle design specification.

4. Research Objectives

The aim of the EngD research was to develop the techniques that would enable a Sound Quality Engineering Process to be introduced to Jaguar Cars. The purpose of introducing such a process was to develop a structured means of incorporating the delivery of Sound Quality within the vehicle development process. This process was to address two specific deliverables identified from the previous review of the status of NVH and Sound Quality at Jaguar:

1. How can Sound Quality be used to deliver Jaguar's core-mark value of Refined Power to support and enhance the Jaguar brand image?
2. How can the Jaguar brand requirements for Refined Power be translated into engineering design specifications?

In order to achieve these two deliverables a number of key elements were identified. These key elements defined the six research objectives outlined below:

1. To develop a means of measuring and quantifying the subjective nature of Sound Quality.
2. To develop a means of targeting the subjective Sound Quality to support the delivery of the Jaguar core-mark value of 'Refined Power' and the individual vehicle programme requirements.
3. To identify the key acoustic features within the vehicle sound signatures that are responsible for generating the difference in the subjective characters between Jaguar's vehicles and those of its competitors.
4. To develop a means of generating an objective vehicle level Sound Quality target that delivers the subjective Sound Quality target and that can be used to drive the vehicle design specification.
5. To develop the technology that is required to deliver the design changes necessary to achieve the vehicle level Sound Quality target.
6. To combine each of these elements into a Sound Quality Engineering Process that is aligned with the existing vehicle development process.

5. Background Literature Review

Prior to developing the technology to deliver the Sound Quality Engineering Process it was necessary to conduct a review of the previously published literature that reported the work of other researchers in the field of Sound Quality Engineering within the automotive industry. This literature review identified two principal clusters of previous work that were to be significant in terms of the research objectives. The first of these was the group of papers that focussed on the quantification of the subjective nature of Sound Quality in terms of a number of underlying factors. The second was the group of papers that focussed on the identification of the acoustic features that were responsible for generating different subjective characteristics. The following section reviews the key findings from each of these two clusters of papers.

5.1 The Underlying Subjective Nature of Sound Quality

The first group of papers were those that attempted to develop an understanding of the underlying subjective nature of Sound Quality. Sound Quality is highly subjective in nature and one means of capturing this subjectivity is through a series of adjectives that can be used to describe the character of the sound. These adjectives, referred to as semantics, include words like Powerful, Sporty, Refined, Harsh, etc. In many of the papers reviewed the researchers collated a list of these semantic descriptors and used them to evaluate the nature of the Sound Quality of vehicle sound recordings replayed over headphones. These studies involved the use of jury appraisals that employed the semantic differential rating system to assess the sounds. The semantic differential rating system was originally developed by Osgood [6] to evaluate the human emotional reaction to semantic words. The principle behind the system is that the perception of a stimulus falls into different dimensions, each defined by a linear semantic space. The extremities of each semantic space are defined by two bipolar adjectives, e.g. Quiet/Loud, Powerful/Weak etc. Between these two extremities there is a scale reflecting the level of each of the adjectives. Figure 4 illustrates a typical seven-point rating scale used to subjectively evaluate the perceived Powerfulness of a sound using the semantic differential assessment technique. The jury subject is asked to subjectively evaluate the Sound Quality according to this scale by selecting the rating that they feel best describes the character of the sound. These ratings are then transferred into numeric values for data processing.

How Powerful is the Sound?

+3	+2	+1	0	-1	-2	-3
Extremely	Very	Somewhat	Neither	Somewhat	Very	Extremely
O	O	O	O	O	O	O
Powerful						**Weak**

Figure 4: Semantic Differential Rating System

The review of the published literature has identified that this semantic differential jury evaluation process has been used by fifteen different researchers to evaluate the subjective nature of vehicle Sound Quality. They have each used a selection of bipolar semantic pairs to evaluate different aspects of Sound Quality.

The next step used by each of these researchers was to analyse the nature of the variation in the sets of ratings for all of the semantic pairs derived from the jury results. Each have examined the nature of this variation through the application of Factor Analysis or Principal Component Analysis, see Kim [7] for details. These are data analysis techniques that can be applied to a set of variables, in this case the list of semantic pairs, with the aim of discovering which sets of these variables form coherent subsets with common characteristics that can be regarded as independent of other subsets with different characteristics. The techniques are used to identify a number of underlying factors that can be used to explain the nature of the variability within the dataset. Each of the researchers applied either Factor Analysis or Principal Component Analysis to the results of their semantic differential jury evaluation listening studies with the aim of identifying the number and the nature of the underlying factors that could be used to explain the variation within their datasets. Table 1 summarises chronologically the findings reported by each of these researchers. The table describes the nature of the sound stimuli used by each researcher in terms of the vehicle or component system source, the engine configuration and the driving conditions. It lists each of the researchers' interpretation of the underlying factors that they have identified along with the cumulative level of the variation within the dataset accounted for by these factors, indicated by the Contribution Ratio %.

Author	Reference	Year	Vehicle / System Type	Engine Type	Driving Conditions	Factor 1	Factor 2	Factor 3	Contribution Ratio %
Kazunori	[8]	1988	Exterior Exhaust	I4	Transient Accel. Ext.	Powerful	Buoyant		62
Nakamura	[9]	1989	Car Interior	N/A	Slow Trans. Accel.	Beauty	Powerfulness	Metallicness	61
Kozawa	[10]	1991	Exterior Exhaust	N/A	St. State & Transient	Powerfulness	Beautifulness		-
Okamoto	[11]	1991	Car Interior	N/A	Transient Accel.	Preference	Powerfulness	Rooughness	70
Takanami	[12]	1991	Car Interior	I4	Transient Accel.	High Grade	Powerful	Metallic	98
Wakita	[13]	1991	Exterior Exhaust	N/A	Transient Accel.	Powerful	Beautiful		-
Otto	[14]	1992	Car Interior	N/A	Transient Accel.	Smooth	Powerful	Loud	65
Hashimoto	[15]	1993	Car Interior	I4	Steady State	Pleasantness	Powerfulness	Boomingness	-
Takao	[16]	1993	Car, Van & Truck	N/A	St. State & Transient	Power	Pleasant	Booming	72
Murata	[17]	1993	Car Interior	I4 & I6	Steady State	Comfortable	Powerful	Booming	85
Bisping	[18]	1995	Car & Truck	I4, I6, V8	Transient Accel.	Pleasantness	Power		70
Hashimoto	[19]	1995	Exterior Exhaust	N/A	Idle Exterior	Pleasantness	Powerfulness	Booming	
Kashiwakura	[20]	1995	Car Interior	N/A	Steady State	Pleasant	Light	Booming	-
Terazawa	[21]	1996	Car Interior	I4	Transient Accel.	Annoying	Metallic		82
Bisping	[22]	1997	Car Interior	I4, I6, V8	Transient Accel.	Pleasantness	Power	Bright/Impluse	73
Buss	[23]	1999	Car Interior	N/A	Steady State	Comfort	Power	Sonority	66
Sato	[24]	1999	Truck Exterior Idle	I6	Idle Exterior	Comfortability	Powerfulness		93

Table 1: Summary of Underlying Sound Quality Factors Identified from Reviewed Literature

Table 1 illustrates that all of the researchers identified either two or three underlying dimensions, or factors, that were responsible for the variation within the dataset. The most significant finding from the papers reviewed is that all but four of the researchers identified two underlying dimensions that describe the same characteristics. The first of these represents the strength or the power aspect of the sounds, interpreted as Power, Powerful or Powerfulness. The second represents the comfort related aspects of the sounds, interpreted as Beauty, Beautifulness, High Grade, Pleasantness, Comfort and Comfortable. The third factor identified by a number of the different researchers varies in nature, with some referring to it as a metallic factor, and others referring it to as a booming factor. However, there is no common agreement between the different researchers on the nature of this third factor. It may be concluded therefore that the review of the previous literature has identified that the nature of Sound Quality can be expressed in terms of two underlying dimensions; a measure of the relative strength or power of the sound and a measure of the relative comfort of the sound. There may be another dimension but there is disagreement on the definition of this dimension.

A critical review of the work of these researchers has identified a number of significant concerns with the findings and conclusions reported. A full review of these concerns is detailed in the submission to the EngD portfolio titled *Sound Quality Brand Engineering* [25], but the following summarises the key concerns identified from the review. The first concern relates to the nature of the stimuli used in the evaluation. The papers by Hashimoto [15] & [19], Murata [17], Kashiwakura [20] and Buss [23] only evaluated steady state sound stimuli. They did not evaluate transient accelerating operating conditions and without this the author believes that it is not possible to evaluate the nature of Powertrain Sound Quality, as perceived by the customer. In the papers by Kazunori [8], Kozawa [10], Wakita [13], Hashimoto [19] and Sato [24] the stimuli used were recordings of exterior exhaust tailpipe orifice noise. Whilst this is an important aspect of Sound Quality, the findings established for exterior Sound Quality do not necessarily translate into the requirements for vehicle interior Sound Quality, which is the focus of the EngD research.

The next significant concern with the papers reviewed relates to the level of variation accounted for by the identified underlying factors or dimensions. One of the most important aspects of Factor Analysis or Principal Component Analysis is the interpretation of the results. The mathematical analyses will always identify a number of factors or principal components, but the significance of each of these factors is based upon the amount of the variation accounted for by each factor, and by the total level of variation accounted for by all of the *significant* factors. The interpretation of the results of the analyses to identify those factors that are significant and that represent the true nature of the variation is the most important aspect of the analyses. There are a number of tests that can be conducted on the results of the analyses to establish the level of significance for each of the derived factors, such as comparing the proportion of the variation accounted for by the different factors or by examining the level of variation accounted for by each factor and comparing it with the expected level of variation. Each of these tests of significance is detailed in the submission to the EngD portfolio titled *Sound Quality Brand Engineering* [25].

Unfortunately, however, none of the papers reviewed used these tests of significance to validate their conclusions. As a result it is not possible to confirm that the factors that they have identified are representing the true underlying nature of Sound Quality. In particular in the papers by Nakamura [9], Okamoto [11], Otto [14] and Bisping [22], the total level of the variation accounted for by each of the factors was relatively small, with values between 61 to 70%. This would imply that their analyses had only accounted for two-thirds of the total variation within the dataset. In addition, as they had not supplied a detailed breakdown of the contribution of each factor it is not possible to test the significance of their results. Consequently the findings reported by each of these researchers cannot be validated and they should be taken with caution. In the papers by Hashimoto [19] and Kashiwakura [20] the researchers did not even report the total level of the variation accounted for, and consequently their results also must be taken with caution.

The next concern with the papers reviewed relates the nature of the engine configurations used in the studies. In each of the studies by Kazunori [8], Takanami [12], Hashimoto [15] and Terazawa [21], all the stimuli were recordings from vehicles fitted with I4 engine configurations. The purpose of the EngD research was to develop a process for delivering the Sound Quality of vehicles fitted with V6 and V8 engine configurations, i.e. the engine variants produced by Jaguar that compete in the luxury vehicle sectors. Consequently the findings established by each of these researchers on I4 engines may not reflect the nature of the Sound Quality within the luxury vehicle sectors. In many of the other papers, the engine configurations were not even reported, and consequently the findings from all of these papers also may not reflect the nature of the Sound Quality within the luxury vehicle sectors.

The most significant concern with all of the papers reviewed however is that they have each only attempted to identify the underlying nature of the Sound Quality of sound stimuli replayed to jury subjects within an artificial laboratory environment. The customer does not experience Sound Quality in this environment, but rather bases his/her assessment of Sound Quality on actual drive evaluations of the vehicle in the real world. None of the papers have therefore identified the underlying nature of Sound Quality as perceived by the customer. This is felt to be a significant oversight by each of the researchers. There may indeed be a link between the laboratory based jury evaluations and actual vehicle drive appraisals, but none of them have attempted to either confirm or quantify this link. It may be concluded therefore that although the aim of each of the papers reviewed was to identify the underlying nature of Sound Quality within their datasets, they did not identify the underlying nature of Sound Quality as perceived by the customer.

In summary, a number of concerns have been identified with each of the papers reviewed. None the findings established could be verified, and in most cases they do not necessarily reflect the nature of the Sound Quality within the luxury vehicle sectors. Of most significance they are also only based upon analyses of the results of jury listening studies and not actual vehicle drive appraisals, and consequently may not reflect the customer's perception of Sound Quality. Nevertheless the fact that each of these papers individually indicated that the subjective nature of Sound Quality could be represented by a number of underlying dimensions is a significant finding.

5.2 Identification of Key Acoustic Features

The second significant cluster of work identified from the literature review were those papers that focussed on the identification of the acoustic features in the sound signatures of the vehicles that were responsible for determining the different subjective characteristics. The review identified seven different acoustic features that had previously been found to be responsible for different subjective characteristics. These seven acoustic features were 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 or a Measure of the High Frequency Content in the sound, and the Impulsiveness. A detailed review of each of these acoustic features and the findings established by the different researchers is included in the EngD submission titled *Understanding the Sounds and Objective Sound Quality Target Setting* [26]. The following section summarises the key findings of this review.

Table 2 chronologically lists each of these acoustic features against the papers in which they have been identified, and relates each feature to the two underlying dimensions of Sound Quality that had been suggested from the review of the papers that attempted to identify the underlying nature of Sound Quality. These two dimensions had been described as a measure of the relative strength of the sound, and a measure of the relative comfort of the sound. Within each of the papers reviewed the acoustic features identified were related by the researchers to either of these two underlying dimensions. The '**Strength**' and '**Comfort**' words in Table 2 reflect the relationship between the seven acoustic features and each of the two underlying dimensions of Sound Quality established by the researchers.

The development of an understanding of the effect of key acoustic features on the difference in the subjective Sound Quality perception between Jaguar's own vehicles and those of its competitors was one of the specific objectives of the research. As a result each of the seven acoustic features were reviewed with view to relating them to the Sound Quality aspects of Jaguar's range of vehicles.

Author / Acoustic Feature	Reference	Year	Roughness / Rumble	Linearity	Dominant Firing Order (I4=2E , I6=3E)	LowOrders Sound Pressure Level	Loudness	Sharpness / High Frequency Content	Impulsiveness
Callow	[27]	1979				Comfort	Comfort	Comfort	
Tsuge	[28]	1985	Comfort						
Townsend	[29]	1985							Comfort
Aoki	[30]	1987	Comfort	Comfort					
Russell	[31]	1987							Comfort
Kazunori	[8]	1988			Strength				
Wakita	[13]	1991				Strength	Strength		
Kozawa	[10]	1991				Strength			
Takanami	[12]	1991	Comfort		Strength		Comfort		
Hussain	[32]	1991	Comfort				Comfort	Comfort	Comfort
Hutchins	[5]	1992	Com / Str			Strength			
Hashimoto	[15]	1992	Comfort				Strength		
Murata	[17]	1993				Strength		Comfort	
Takao	[16]	1993	Comfort						
Schneider	[33]	1995	Comfort	Com / Str		Comfort	Comfort	Comfort	
Ohsasa	[34]	1995			Strength			Comfort	
Bisping	[22]	1995		Strength		Com / Str			
Hashimoto	[19]	1995	Comfort				Strength	Comfort	
Maunder	[35]	1995	Strength						
Terazawa	[21]	1996	Comfort			Comfort		Strength	
Blommer	[36]	1997					Strength		
Widman	[37]	1998	Com / Str				Comfort	Comfort	
Brandl	[38]	1999	Comfort			Comfort	Comfort	Comfort	
Biermayer	[39]	1999	Strength		Strength				
Ronacher	[40]	1999	Comfort			Comfort	Comfort	Comfort	
Naylor	[41]	2000	Strength		Strength				

Table 2: Summary of Key Acoustic Features Identified from Reviewed Literature

Within the reviewed literature the acoustic feature that has been referred to the most by the researchers is Roughness or Rumble. Tsuge [28] defines Rumble as the discomforting sensation that is heard intermittently and impurely during acceleration. It is due to the presence of closely coupled half engine orders (tones) that cause a beating sensation to be generated in the time envelope. Twelve of the researchers associated rumble with the comfort related aspects of Sound Quality, with the assumption that higher levels of Rumble degrade the refinement or comfort of the vehicle. However, a number of other researchers have also highlighted the importance of Rumble in contributing towards the strength or powerful aspects vehicle sounds. In these papers it was found that increasing the level of Rumble enhances the sporty or powerful Sound Quality characteristics. It would appear therefore that Rumble can affect both of the suggested underlying dimensions of Sound Quality. However, there has not been any reported study that has investigated how much Rumble would be required to generate a powerful or a sporty Sound Quality character without adversely affecting the comfort related aspects of Sound Quality. This has been identified as a significant gap in the previously published literature, and was an area that was felt to be of major significance to Jaguar in the delivery of the core-mark value of 'Refined Power'.

The second acoustic feature that was found to influence the subjective perception of Sound Quality is Linearity. Aoki [30] confirmed that extreme changes in the overall sound pressure level as the vehicle accelerates can result in an unpleasant sensation that degrades the comfort related aspects of Sound Quality. However, a number of other researchers, notably Bisping [22] and Schneider [33] indicated that initial steep changes in the level of the low frequency content of a sound can increase the perception of the strength of the sound and enhance its powerful characteristics.

The third acoustic feature identified was the influence of the engine firing order. The importance of the primary engine firing order to the strength or powerful subjective aspects of Sound Quality was identified by each of Kazunori [8], Takanami [12], Ohsasa [34], Biermayer [39] and Naylor [41]. However, each of these studies was based upon an analysis of the engine firing orders 2E and 3E from vehicles fitted with I4 and V6 engine configurations. There has not been any reported investigation into the influence of the firing order 4E on vehicles fitted with V8 engine configurations.

The fourth acoustic feature identified to influence the subjective perception of Sound Quality was the Sound Pressure Level of the low engine orders. Like Roughness or Rumble this acoustic feature was found by some of the researchers, namely Schneider [33], Terazawa [21], Brandl [38], Ronacher [40], Maunder [35] and Callow [27] to degrade the comfort related aspects of Sound Quality, but was also found by other researchers, namely Wakita [13], Kozawa [10], Hutchins [5] and Murata [17] to increase the perception of the strength of the sound. The level of the low engine orders would therefore be an important consideration in delivery of the Sound Quality of Jaguar's vehicles.

The fifth acoustic feature was identified as the Loudness level. The Loudness level is one of the most basic psychoacoustic measures. It provides a measure of the intensity of a sound. The intensity of the sound as expressed through the Loudness level was identified by each of Callow [27], Takanami [12], Hussain [32], Schneider [33], Widman [37], Brandl [38] and Ronacher [40] to degrade the comfort related aspects of Sound Quality, with Louder sounds invariably sounding more annoying. However, each of Wakita [13], Murata [17], Hashimoto [19] and Blommer [36] have indicated that an increase in the Loudness level enhances the perception of the strength of the sound and can help to convey an increased perception of powerfulness. The influence of the Loudness level on the Sound Quality perception of Jaguar's vehicles would therefore also need to be considered.

The sixth acoustic feature found to influence the subjective perception of vehicle sounds was identified as Sharpness. Sharpness essentially provides a measure of the high frequency content of a sound. Increased levels of Sharpness were identified by each of Callow [27], Hussain [32], Murata [17], Schneider [33], Hashimoto [19], Widman [37], Brandl [38] and Ronacher [40] to degrade the comfort related aspects of Sound Quality. In addition, Terazawa [21] suggested that low levels of Sharpness could contribute towards an increased perception of the strength of the sound. The influence of Sharpness on the Sound Quality perception of Jaguar's vehicles was also identified as an area that would need to be investigated.

The seventh and final acoustic feature that was identified through the literature review to influence the subjective perception of vehicle sounds was defined as Impulsiveness. Impulsiveness provides a measure of the irregularity in a vehicle sound, which is perceived primarily in the time domain. Impulsiveness was found to be a key acoustic feature by each of Hussain [32], Russell [31] and Townsend [29], in particular in relation to the impulsive nature of diesel engine variants. For petrol engines however, the literature review has not identified it to be a significant acoustic feature. As the focus of the EngD research was to be on V8 petrol engines the level of Impulsiveness was therefore not considered to be an area that warranted investigation.

5.3 Sound Quality as an Engineering Process

One of the most important findings from the background literature review was the lack of any paper that looked at Sound Quality as an engineering process. None of the papers reviewed demonstrated how the individual findings established from the different areas of research into Sound Quality could been incorporated into a Sound Quality Engineering Process that links the subjective nature of Sound Quality to the vehicle development process. The lack of any evidence of the development and implementation of such a structured process to Sound Quality Engineering is felt to be a significant shortfall in the Sound Quality work that has been previously published.

5.4 Summary of Background Literature Review Findings

The review of the previously published literature had identified a number of areas that would require further investigation in the development of the Sound Quality Engineering Process. In particular the concept of quantifying the subjective nature of Sound Quality in terms of semantic descriptors was seen to be an area that could provide a link between the customer requirements and the Sound Quality target setting process. The use of Factor Analysis to identify the underlying nature of Sound Quality based upon then level of variation amongst these semantic descriptors was also seen to be a very useful concept. However, the two underlying dimensions of the strength and the comfort related aspects of Sound Quality that had been proposed by many of the papers would need to be revisited and if possible verified. In particular the identification of the underlying nature of the Sound Quality within the luxury vehicle sector would need to be established within the context of how the customer perceives Sound Quality.

The identification of the acoustic features that had previously been found to influence the subjective perception of vehicle sounds has also been a significant finding from the literature review. Each of the acoustic features Rumble, Linearity, the level of the Firing Order, the level of the Low Engine Orders, the Loudness and the Sharpness would need to be considered in the development of the Sound Quality Engineering process. Finally the lack of any paper that reported on the application of the findings of the Sound Quality research into a structured framework within the vehicle development process was felt to be a significant shortfall in the Sound Quality work that has previously been published.

6. Methodology

This section of the Executive summary details the work that was conducted to develop the techniques to deliver the Sound Quality Engineering Process. It reports on the individual work packages that were formulated to deliver each of the research objectives outlined in Section 4.

6.1 Formulation of the Initial Concept Sound Quality Engineering Process

As a starting point in developing the new Sound Quality Engineering Process, a concept process was developed to guide the direction of the EngD research. This concept process, illustrated in Figure 5, identified a number of steps that were needed to address each of the six research objectives. It was used as the basis for defining the individual work packages of the EngD research programme.

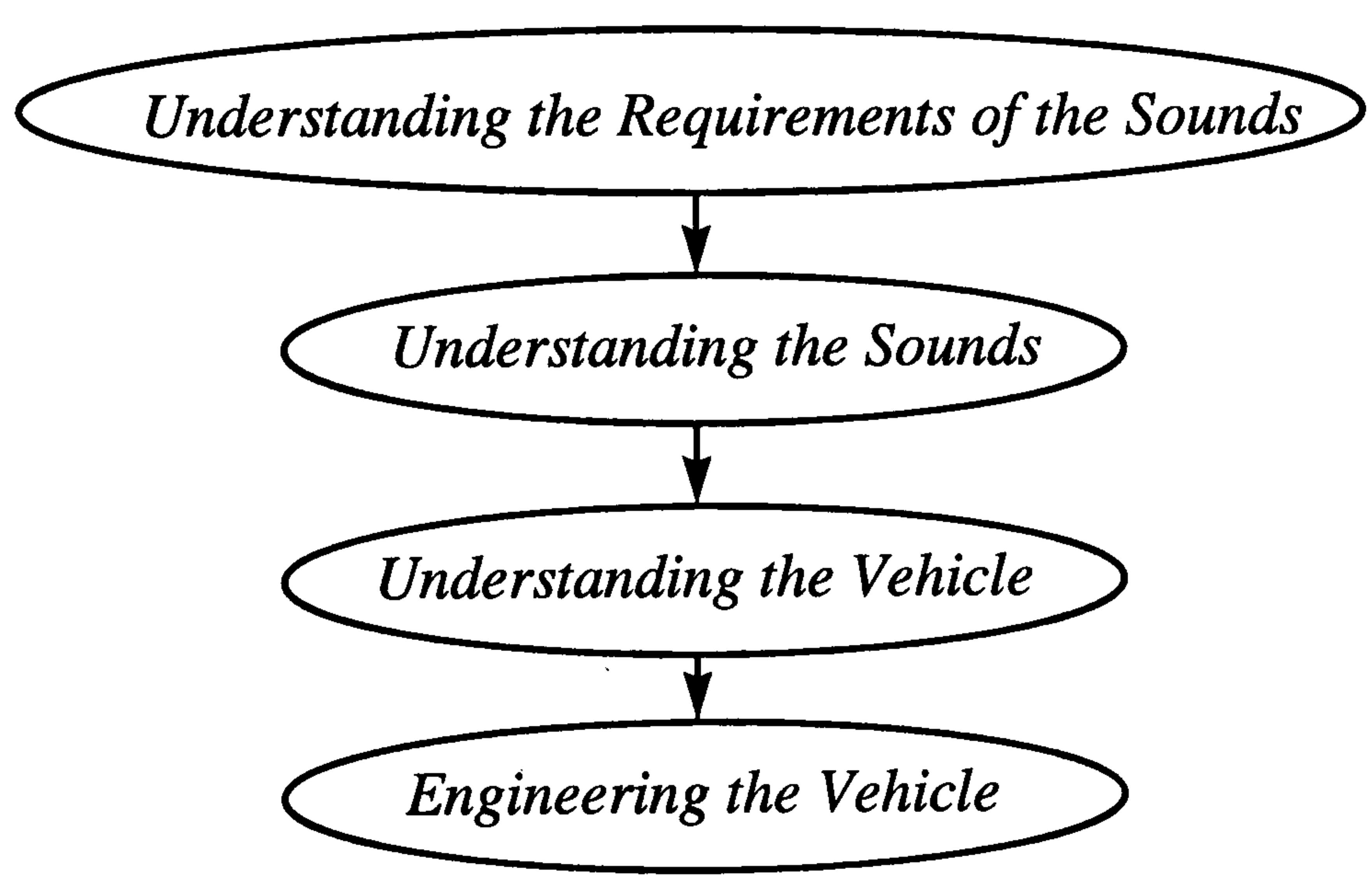


Figure 5: Initial Sound Quality Engineering Process Concept

The first step in the concept process was referred to as *Understanding the Requirements of the Sounds*. The purpose of this step was to establish the state of the competition and the existing Jaguar product range in terms of the subjective differences in Sound Quality perceived by the customer. These differences were then to be used to develop a subjective Sound Quality target character for a new vehicle programme. This step in the process was formulated to address the first and second research objectives outlined in Section 4. The second step in the process was referred to as *Understanding the Sounds*. The purpose of this step was to identify the key acoustic features within the sound signatures of the vehicles that are responsible for determining the differences in subjective character. It was formulated to address the third research objective outlined in Section 4. The third step in the process was referred to as *Understanding the Vehicle*. The purpose of this step was to develop an understanding of the design detail in the vehicle that is responsible for generating the key acoustic features, and how predicted modifications to this design detail could affect the vehicle level subjective Sound Quality character. It was formulated to address the fourth research objective outlined in Section 4. The fourth step in the process, *Engineering the Vehicle,* involved identifying the NVH development technology that could be applied within the vehicle development process to deliver the subjective vehicle level Sound Quality target. It was formulated to address the fifth research objective outlined in Section 4.

Each of these four steps were formulated into a structured process that could be integrated within the existing Ford Product Development Process. The formulation of a Sound Quality Engineering Process that was aligned to the vehicle development process was the sixth research objective outlined in Section 4. The initial concept Sound Quality Engineering Process was therefore formulated as a starting point for addressing each of the six research objectives.

6.2 Selection of a Vehicle Programme to develop the Process

In order to develop the Sound Quality Engineering Process such that it could be incorporated with the vehicle development process it was necessary to select a new vehicle programme at Jaguar in which each of the steps of the new concept process could be developed and validated. At the outset of the EngD research programme in 1997 Jaguar had just approved the development of a new vehicle to replace the existing XJ8 large luxury saloon. This new vehicle, codenamed X350, was scheduled for launch in 2002. The timing of the development of this vehicle programme was seen to align with the expected timing of the development of each of the steps of the Sound Quality Engineering Process over the duration of the EngD research programme. Consequently it was decided that the X350 vehicle programme at Jaguar would be the one through which the steps of the Sound Quality Engineering Process would be developed. The X350 vehicle programme would then act as the pilot application programme to validate the techniques developed to deliver each step in the process. The remaining sections of this chapter detail the research work that was conducted to develop the steps of the Sound Quality Engineering Process through its application on the X350 vehicle programme.

6.3 Understanding the Requirements of the Sounds

The first step in the concept Sound Quality Engineering Process was the development of an understanding of the requirements for Sound Quality. This involved establishing the nature of the difference in Sound Quality between Jaguar's existing vehicles and those of its competitors as perceived by the customer. The important aspect of this stage in the process was to be able to quantify the subjective nature of these customer perceived differences. As a result it was necessary to collate the existing information that quantified these subjective differences.

6.3.1 Market Research

The most important aspect of the Sound Quality Engineering Process was that it captured the differences in Sound Quality that are perceived by the customer. As a result the first step was to collate the existing data that captured the customers assessment of the Sound Quality of the XJ8 vehicle and its competitors. As part of the X350 vehicle programme a market research survey was conducted to solicit in-market customer information. It was possible to include within this survey a number of questions that provided information on the customers' impression of the Powertrain Sound Quality. Information on each of the principal competitors in the large luxury vehicle segment was collected. These vehicles included the Jaguar XJ8, BMW740, Lexus LS400, Mercedes S420 and Audi A8. The surveys were conducted in each of Jaguar's principal markets, the UK, the US and Germany. The detail of this market research survey is included in the submission to the EngD portfolio titled *Subjective Sound Quality Target Setting* [4].

The results of the survey were collated and analysed to identify statistically significant differences between the Sound Quality of the vehicles as perceived by the customers. The most significant findings from this analysis were that in each of the markets the BMW740 was rated by the customers to have the most preferred engine sound, whilst the Jaguar XJ8 was rated to have the least preferred engine sound. This is illustrated in Figure 6, which summarises the key findings of the market research surveys.

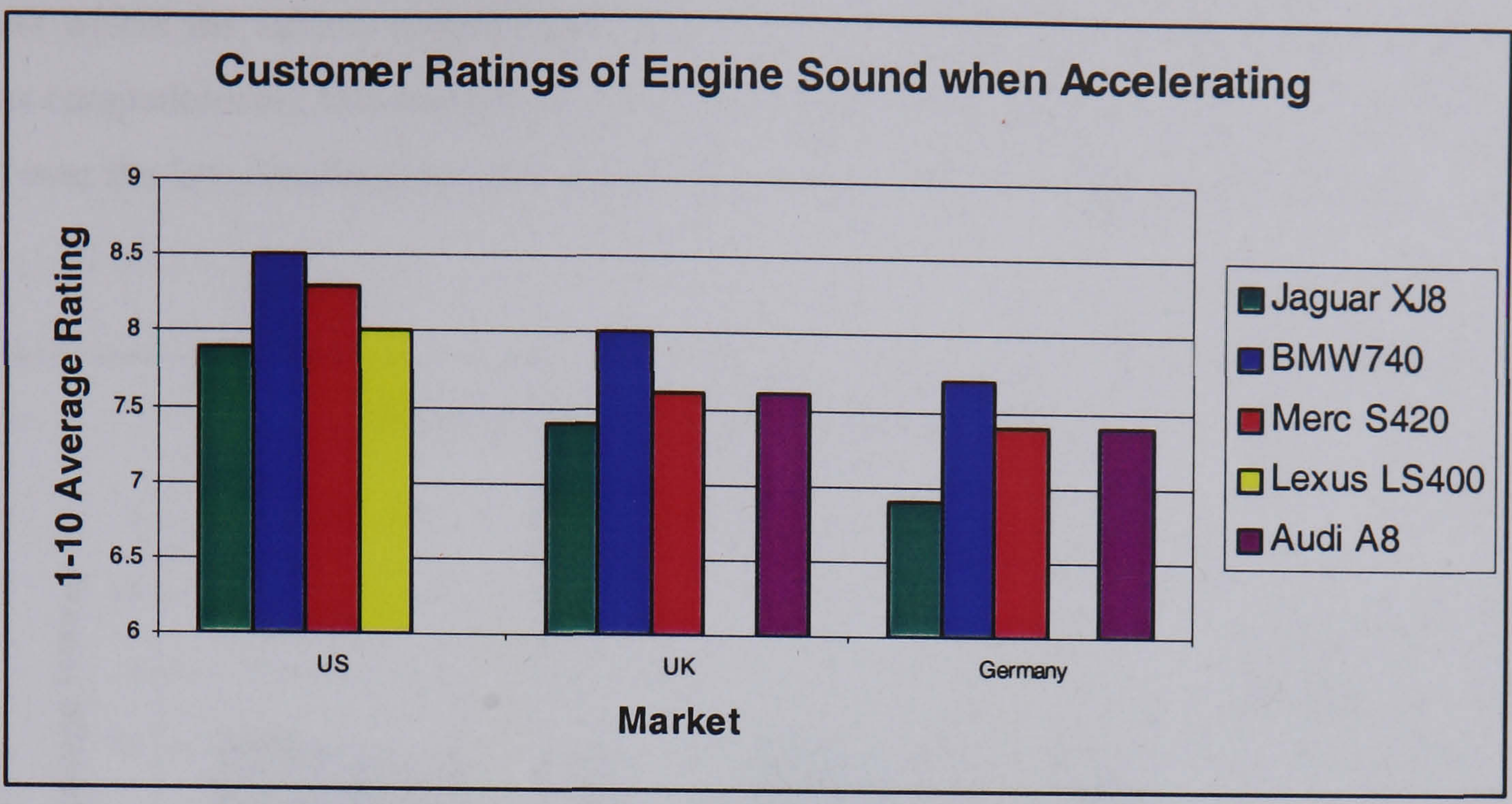


Figure 6: Summary of Customer Evaluations of Sound Quality

This information indicated that the Jaguar XJ8 was trailing the competition in the delivery of the Sound Quality aspects of vehicle refinement. The other piece of information supplied through the market research surveys was the perception of the imagery associated with each of the vehicles. The analysis of these results indicated that the BMW740 was also found to have the highest ratings for each of the imagery characteristics *Powerful, Sporty, Fun-to-Drive, Spirited, Exciting and Aggressive*. The high ratings for these perceived imagery semantics served to complement the preference for the engine sound expressed by the customers for the BMW740. The Jaguar XJ8 on the other hand, in addition to trailing in terms of Sound Quality, did not match the perceived imagery ratings of the BMW740. This was the first significant piece of evidence that the existing XJ8 was not delivering the required image and refinement levels to support the delivery of the brand's core-mark value of Refined Power.

6.3.2 Internal Vehicle Appraisals

The next source of information that was reviewed was the assessment of the NVH and Sound Quality of the existing Jaguar and competitor vehicles conducted in-house by Jaguar's own team of expert vehicle assessors. This group of expert assessors is referred to as the Vehicle Appraisal Group (VAG). The purpose of the VAG is to assess all of the vehicle level functional performance attributes, such as Ride, Handling, Steering, etc., and includes an assessment of the Powertrain NVH using a 1-10 rating scale system. These results are used to drive the target setting process within the vehicle development process. The VAG assessment results for the Jaguar XJ8 and its competitors are illustrated in Figure 7, for each of the sub-attribute categories of Powertrain NVH over the low / mid engine speed range and over the mid / high engine speed range.

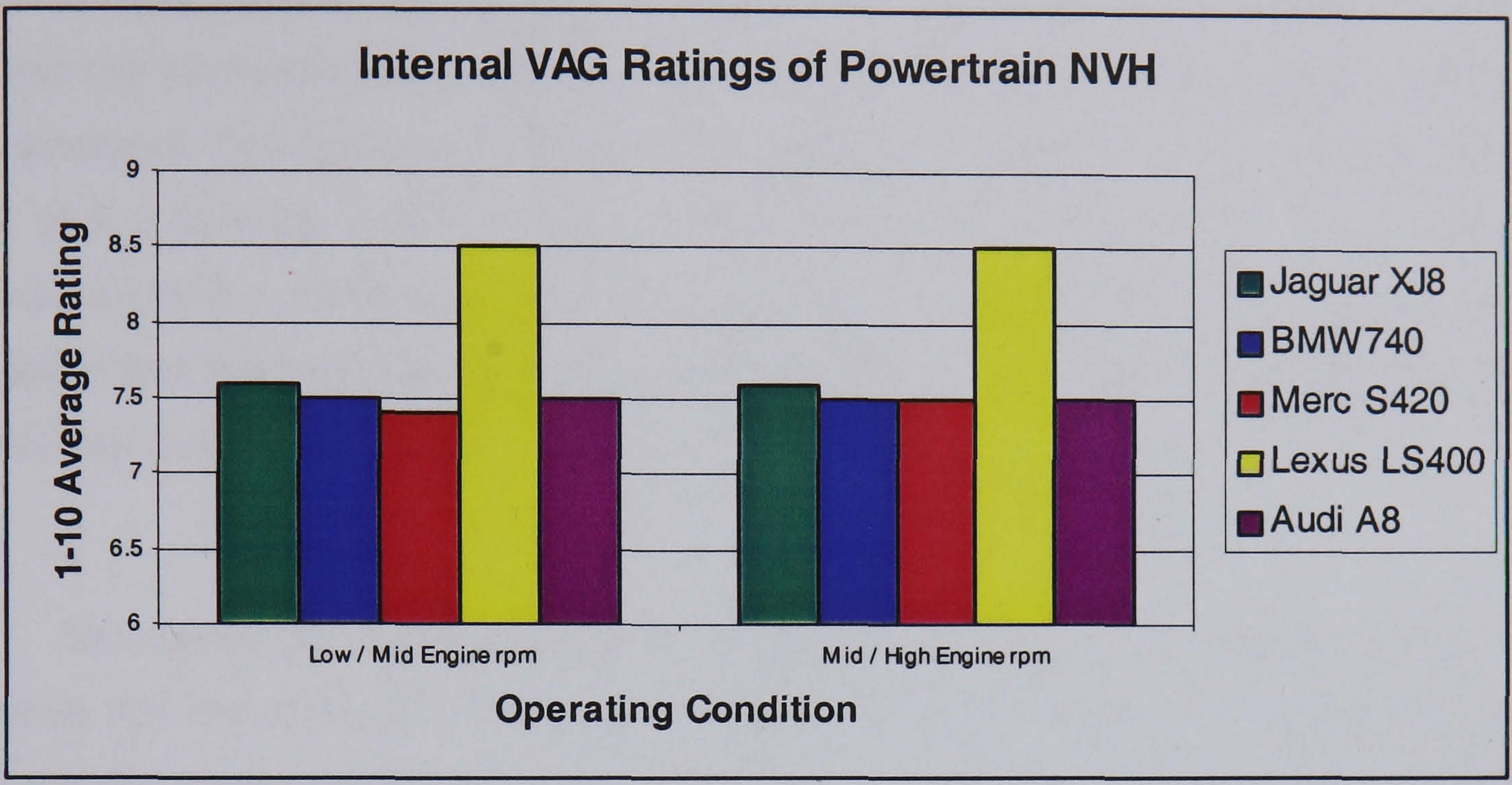


Figure 7: VAG Ratings of the Powertrain NVH Vehicle Level Attribute

The most significant conclusion from the analysis of these results is that the VAG process identified the Lexus LS400 as the vehicle with the highest Powertrain NVH ratings. This is in contrast to the customer-derived results from the market research surveys, which had identified the BM740 as the vehicle with the most preferred engine sound. In addition the VAG process had failed to indicate that the XJ8 had the least preferred engine sound of all the vehicles, as had been indicated by the customers. It can be concluded therefore that the existing VAG process was not structured to capture the customer requirements for engine Sound Quality. The reason for this was that the VAG process was not evaluating the Sound Quality, but was merely assessing the overall noise levels. These overall noise levels are important, but they are not the means through which the customer evaluates the refinement of the engine sound. Previously these VAG results had been used to define the initial vehicle level targets for a new vehicle programme. This was the first step in the vehicle development process. However, it has been demonstrated that these targets do not reflect the customer requirements and as a result it can be concluded that the entire vehicle development process had not been structured to develop the vehicle to meet the customer level requirements for NVH.

6.3.3 Jury Listening Studies

The previous comparison between the customer assessments of Powertrain Sound Quality and the internal VAG assessments of Powertrain NVH demonstrated that the NVH target setting process at Jaguar had not been focussed on delivering the customer level requirements. It was clear therefore that an alternative approach for targeting these customer level requirements would need to be developed. To begin the development of this alternative approach it was decided to conduct a series of jury listening studies with the aim of identifying the reasons why the customers had expressed subjective preferences for the Sound Quality of the BMW740. If these reasons could be established then this would be the first step in the definition of a Sound Quality target that captures the customer level requirements.

The review of the background literature had identified two different types of jury appraisals that had previously been used to evaluate the Sound Quality of vehicles. The first of these was the semantic differential system that was described in Section 5.1. The purpose of this form of jury appraisal is to identify the differences in the Sound Quality character between different vehicles, expressed in terms of semantic descriptors, e.g. Powerful, Sporty, Refined etc. The second type of jury appraisal system that had been commonly used was the paired comparison of preference system. In this system the jury subjects are asked to make relative judgments on sound stimuli presented to them in pairs. Every stimulus from a given set of stimuli is compared with every other stimulus so that all possible comparisons are evaluated. The results of the paired comparisons can be analysed to produce merit scores that provide measures of the relative differences between the stimuli. Refer to David [42] for further detail on the paired comparison system and merit scores. Alternative forms of jury appraisals were considered, including rank ordering and rating scales, but it was decided that as a result of the previous successful application of the semantic differential and the paired comparison of preference systems identified through the reviewed literature, that these two forms of jury appraisal would be most suited to the evaluation of the Sound Quality of the XJ8 vehicle and its competitors.

A series of jury listening studies were developed to compare the Sound Quality of sounds recorded in each of the five vehicles previously mentioned undergoing a 2nd Gear Wide Open Throttle (2GWOT) acceleration. This operating condition is widely used throughout the automotive industry to capture the Powertrain NVH performance over the full operating speed of the engine. The semantic differential test involved assessing the Sound Quality of each vehicle using eight different bipolar semantic pairs. The pairs selected were those that were felt to be important to capture the core-mark value of Refined Power, and were also those which other researchers had previously identified to be appropriate in the evaluation of Powertrain Sound Quality. Jury subjects selected from Jaguar employees were chosen to conduct the evaluations. The sounds were replayed to these jury subjects over headphones in a quiet environment. The results of the jury appraisal were analysed using tests of significance such as ANOVA and the Student's t-test to identify those semantics that could be used to differentiate between the Sound Quality of the five vehicles. The submission to the EngD portfolio titled *Subjective Sound Quality Target Setting* [4] details this analysis. It identified that six of the eight semantic pairs could be used to quantify the nature of the differences in Sound Quality between the five vehicles. The average results for each of the semantics for each vehicle are illustrated in Figure 8.

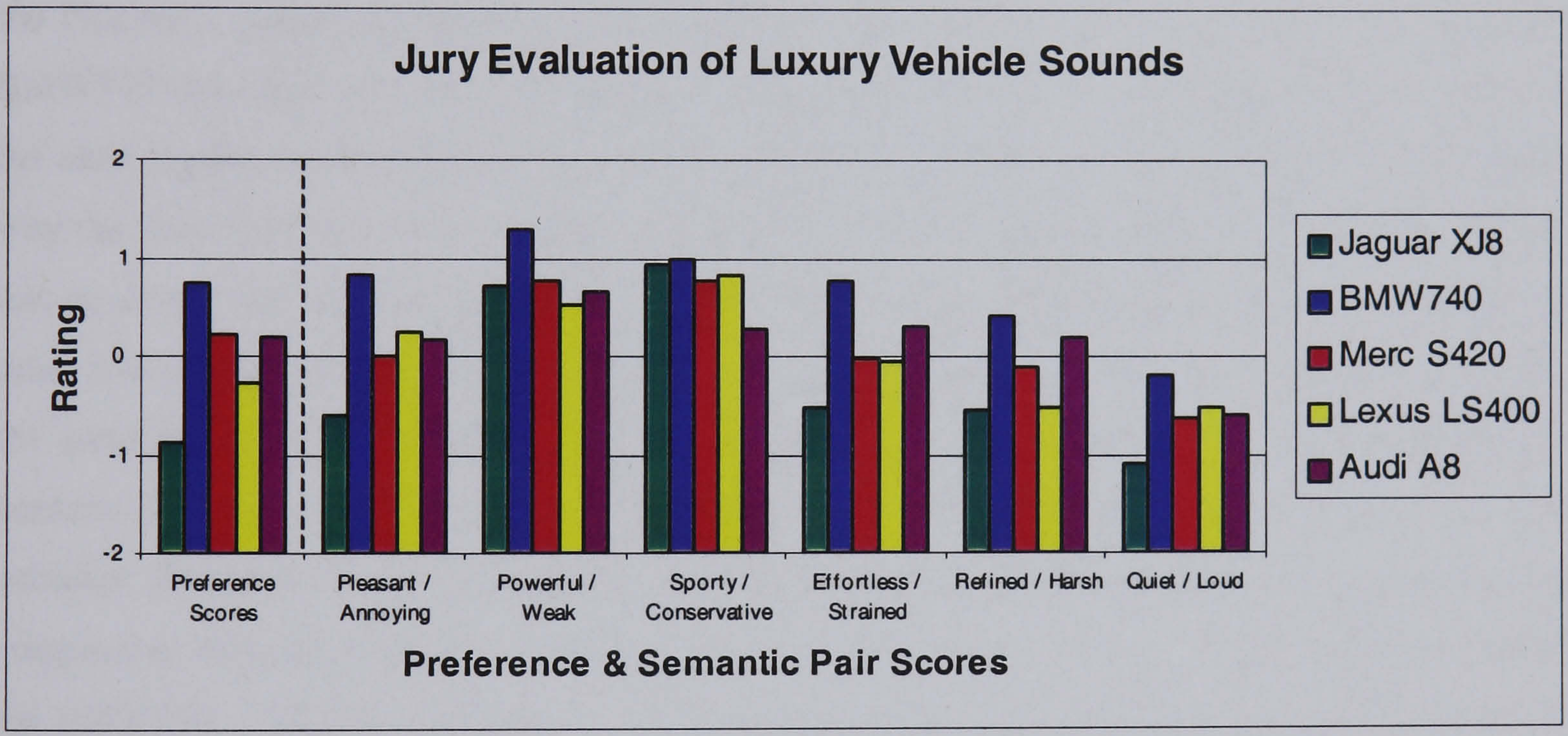


Figure 8: 2GWOT Jury Evaluation Results

For the paired comparison of preference jury test the 2GWOT sound recordings from each vehicle were compared with the sound recordings from every other vehicle, and the jury subjects were asked to select which of the two sounds presented to them in pairs did they prefer. Checks on the levels of consistency and repeatability were conducted to confirm the validity of the results from each jury subject. The preference merit scores calculated from the results of the study are illustrated as the first set of bars in Figure 8. It is worth noting that in each of the tests the jury subjects were unaware of the source of each of the sound stimuli, i.e. the assessments were blind.

The first significant finding from the jury appraisals was that the BMW740 was evaluated to be the most preferred of all of the vehicle sounds, and that the Jaguar XJ8 was evaluated to be the least preferred. This was the same finding established from the market research surveys. If all of the preference merit score results from the jury appraisals are compared with all of the customer ratings for Sound Quality from the market research surveys, correlation coefficient values of 0.97, 0.89 and 0.99 for each of the US, UK and German markets respectively are achieved. These are extremely high levels of correlation. Indeed the critical correlation coefficient at the 95% significance level for this number of variables is 0.87, and at the 99% significance level is 0.95. These highly significant levels of correlation imply that the results of the internal jury appraisals are reflecting the preferences for Sound Quality expressed by the customers.

The preference merit scores derived from the paired comparison test reflect the ratings for the Pleasant / Annoying semantic pair established from the semantic differential test. Again the BMW740 was rated to be the most preferred and the Jaguar XJ8 to be the least preferred. However, the most significant finding from the semantic differential study was the description of the reasons why the BMW740 was the most preferred and the most pleasant, and why the Jaguar XJ8 was the lest preferred and the most annoying. This information was supplied through the ratings for the other five semantics. Figure 8 illustrates that the BMW740 was evaluated to be the most Powerful, the most Sporty, the most Effortless, the most Refined and the Quietest of all the vehicles. In contrast the XJ8 was evaluated to be the most Strained the Harshest and the Loudest of all the vehicles. It was however rated to be second only to the BMW for the Sporty semantic, and comparable with the Mercedes S420 and the Audi A8 for the Powerful semantic but still trailing the BMW740. Using these findings it can be concluded that the reason why the BMW740 was the most preferred was because it was perceived to have high levels of the performance related Sound Quality characteristics of Powerful and Sporty, combined with high levels of the refinement related Sound Quality characteristics of Effortless, Refined and Quiet. The Jaguar XJ8, was the least preferred primarily because of the low levels of the refinement related Sound Quality characteristics, Effortless, Refined and Harsh when compared to all of its competitors, and in addition because it did not display the same levels of the performance related Sound Quality characteristics as the BMW740. This study has provided clear evidence that the Jaguar XJ8 was not delivering competitive levels of Refinement, nor the class-leading levels of Powerfulness demonstrated by the BMW740. The jury studies have therefore provided, for the first time, a means of quantifying the level of achievement in the delivery of the core-mark value of Refined Power, and have demonstrated that the XJ8 was failing to support the delivery of this core-mark value.

6.3.4 New VAG Assessment Process and the Powertrain Sound Quality Profile

The success of the jury appraisals to capture the customer's perception of Sound Quality, and to explain in terms of a number of semantic descriptors the reasons for the differences between the vehicles illustrated that it would be possible to develop a process that could target the Sound Quality for a new vehicle programme. However, one of the issues with the jury appraisals is that they do not represent exactly what the customer experiences. Rather than assessing the Sound Quality through jury listening studies within an artificial laboratory environment, the customer bases his/her assessment of Sound Quality on their experience of actually driving the vehicles. The differences between jury listening studies and actual drive assessments was the same issue that had been highlighted with all of the previously reviewed papers outlined in Section 5.1. In order to be able to set subjective vehicle level targets, and to evaluate the degree of achievement towards these targets, it would therefore be necessary to develop a means of capturing the assessment of Sound Quality, as perceived by the customer. The use of jury listening tests to set the initial Sound Quality targets and to evaluate the final degree of achievement would not be an appropriate means of capturing this customer perspective. Rather the VAG process was seen as the means through which all of the subjective vehicle level targets were set and eventually evaluated, and consequently if a subjective vehicle level target for Sound Quality were to be set, then it would need to be incorporated within the VAG process.

However, it has been demonstrated in Section 6.3.2 that the existing VAG process was not capturing the differences in Sound Quality perceived by the customer. Consequently it was necessary to derive an alternative approach for quantifying the Sound Quality within the VAG assessment process. As the semantic differential part of the jury listening studies had identified the reasons for the difference in Sound Quality between the five vehicles it was felt that the use of a similar semantic differential assessment technique incorporated within the VAG process could be used to capture the nature of the Sound Quality of a vehicle following an actual drive appraisal of that vehicle. A pilot study was therefore initiated with the aim of establishing if the nature of the differences in Sound Quality between the XJ8 vehicle and its competitors could be captured by using the semantic differential assessment technique. A total of twelve semantic bipolar pairs were selected to use for the assessment. The selection of these pairs were based upon the semantics that had previously been found through the jury appraisals to differentiate between the Sound Quality of the vehicles. The six semantic pairs illustrated in Figure 8 were the first six pairs chosen for the assessment. In addition to these six semantic pairs a further six pairs of bipolar adjectives were added to the assessment. These pairs were selected from the imagery semantics previously used in the market research surveys that were felt to be related to the Sound Quality character of the vehicle. These six further semantic pairs were Luxurious / Bland, Comfortable / Uncomfortable, Aggressive / Subdued, Exciting / Boring, Fun-to-Drive / Laborious-to-Drive, and Spirited / Dull.

A semantic differential assessment sheet was formulated using a seven point rating scale between each of the bipolar pairs. This assessment sheet is included in Appendix A. The assessment sheet was used in a pilot study by the VAG team to evaluate the Sound Quality character of a number of vehicles competing in the large luxury vehicle segment. Figure 9 illustrates the average results for each of the semantics for three of the vehicles that were evaluated, displayed in the form of a polar profile plot. This plot was referred to as the Powertrain Sound Quality Polar Profile.

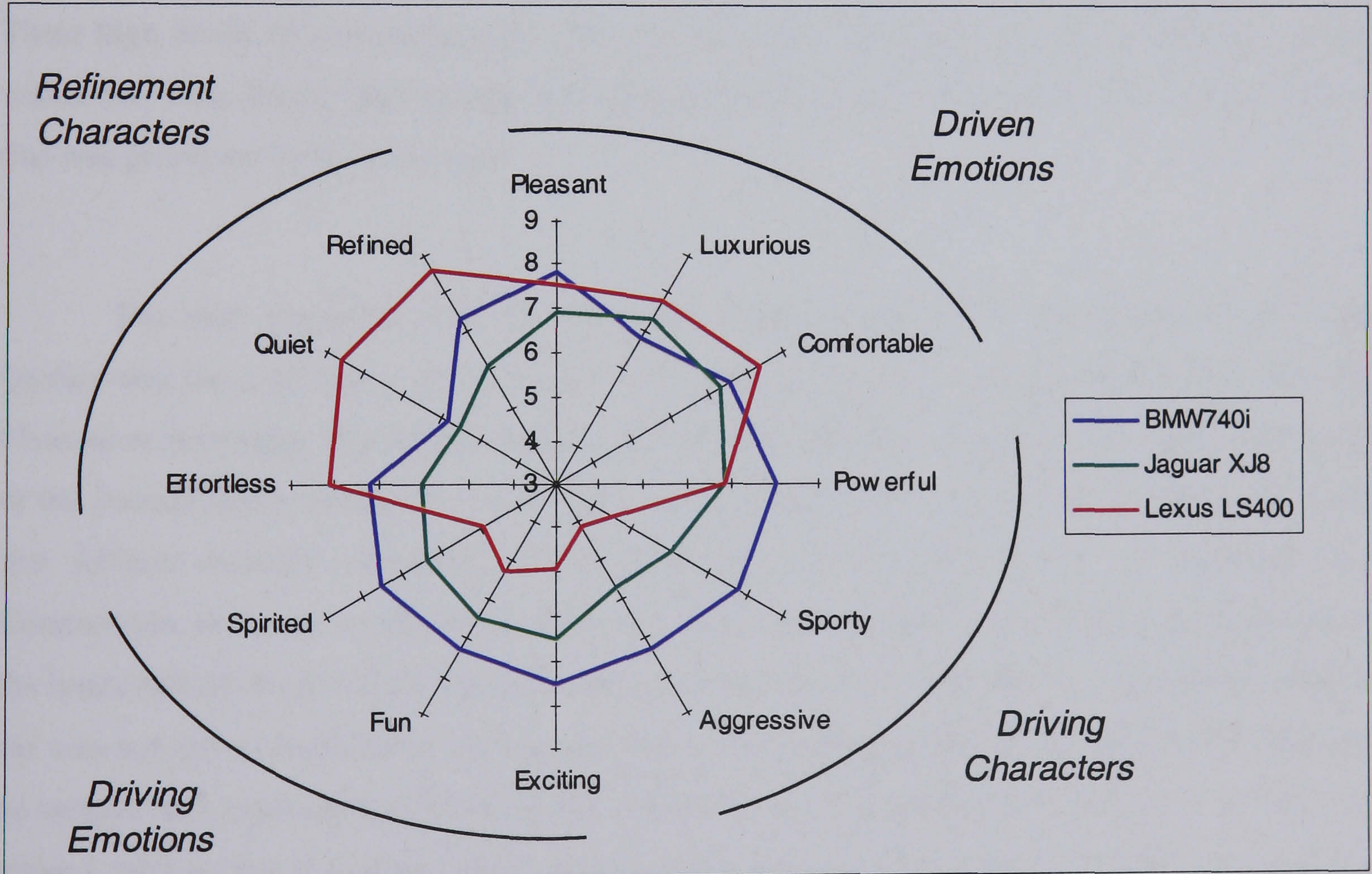


Figure 9: Powertrain Sound Quality Polar Profile Plot

The Powertrain Sound Quality Polar Profile Plot provided a means of illustrating the differences in the nature of the Sound Quality between the different vehicles. The plot illustrates the positive subjective semantic from each of the bipolar pairs, e.g. the Powerful semantic for the

Powerful / Weak semantic pair. The twelve semantics were arranged into four different groups. The Refinement Character and the Driven Emotion groups represent the acoustic and the impressionistic semantics required to achieve a refined vehicle. The Driving Character and the Driving Emotion groups represent the acoustic and impressionistic semantics required to achieve an inspiring and involving driving experience.

It was demonstrated that both the paired comparison of preference merit scores and the Pleasant / Annoying semantic pair ratings from the jury listening studies reflected the customer's overall assessment of the Sound Quality differences between the vehicles. Within the VAG assessment process it is not possible to conduct a back-to-back paired comparison test. It is possible, however, to compare the level of correlation between the Pleasant / Annoying pair from the new VAG semantic differential ratings and the customer ratings of Sound Quality. The correlation coefficient value between each of the US, UK and German market customer ratings, and the VAG Pleasant / Annoying ratings were calculated to be 0.85, 0.97 and 0.99 respectively. These high levels of correlation imply that the Pleasant / Annoying semantic differential ratings within the VAG Sound Quality appraisal process was capturing the differences in Sound Quality that was perceived by the customers.

The most important piece of information supplied from the VAG assessment of Sound Quality was the explanation of the reasons why each of the vehicles was considered to be either Pleasant or Annoying. The Lexus LS400 vehicle within Figure 9 was biased towards the upper half of the Sound Quality Profile. It was evaluated to have high ratings in each of the Effortless, Quiet and Refined acoustic semantics, and consequently the car was felt to be Luxurious and Comfortable. However, it was evaluated to have very low ratings for each of the six semantics in the lower half of the profile. It did not sound Powerful, Sporty or Aggressive, and consequently the car was not felt to be Spirited, Exciting or Fun-to-Drive. The Sound Quality profile can therefore be seen to have captured the Sound Quality character of the Lexus LS400 vehicle. It is a very well refined vehicle, but it is does not possess a sporty or a powerful Sound Quality character. It is worth noting that the Effortless, Strained and Quiet ratings in the Sound Quality Profile are different from the ratings for each of these semantics that were derived through the jury appraisals. This was because the jury appraisals were based only upon the assessment of a full load acceleration run-up. The VAG assessment of Sound Quality was based upon an evaluation of all of the vehicle operating conditions, Idle, Slow Acceleration, Cruising, Fast Acceleration, etc. The VAG assessment can therefore be seen to be more representative of what the customer experiences.

The BMW740 vehicle was evaluated to be the most Pleasant of all of the vehicles assessed. It was found to have high ratings for each of the Powerful, Sporty, Aggressive, Exciting, Fun and Spirited semantics in the lower half of the profile. Although, it was not rated as high as the Lexus LS400 in the Effortless, Quiet and Refined semantics, it was still rated by both the VAG assessors and the customers to have the most preferred or Pleasant Sound Quality character. The Jaguar XJ8 was evaluated to be the least Pleasant of all the vehicles. It was found to trail BMW740 in all of the twelve semantics except for Luxurious. It was rated higher for each of the driver inspiring semantics in the lower half of the profile than the Lexus LS400, but was significantly Louder, less Refined and more Strained than both the BMW740 and the Lexus LS400.

The results of the VAG Sound Quality Profiles have implied that the assessment of the preference in Sound Quality is not based upon the delivery of high levels of the refinement related characteristics, in which the Lexus LS400 excelled, but is rather based upon delivering high ratings for the strength or power related Sound Quality characteristics along with the delivery of competitive levels of refinement. Through its pilot application within the VAG process the Sound Quality Profile was able to capture the differences in the Sound Quality character of the vehicles. As a result the evaluation of Sound Quality using the semantic differential technique was incorporated within the VAG assessment process at Jaguar Cars.

6.3.5 The Use of the Powertrain Sound Quality Profile to Set Sound Quality Targets

The new Powertrain Sound Quality Profile was seen as a useful means of illustrating the Sound Quality character for a given vehicle, and for comparing the Sound Quality characters between different vehicles. One of the requirements of the Sound Quality Engineering process was to use the means through which the Sound Quality was evaluated to define a Sound Quality target for a new vehicle programme. To this end the use of the Powertrain Sound Quality Profile to set such a target was investigated. It was initially proposed to define the target as a new profile that targeted the levels of each of the twelve semantics in the profile against the competition. However, this was not found to be a robust means of setting Sound Quality targets for a number of reasons.

The first of these was the concern with the process used to establish the target Sound Quality Profile relative to the competition. It was proposed that differences between this target and the level of the competition could be based upon the confidence limits established around the ratings for each semantic. These confidence limits were measures of the significant differences between the vehicles and consequently if a new target was defined relative to the confidence band around the semantic rating score for a competitor then there would be a significant and measurable difference between the competitor and the target that would be subjectively perceived by the customer. However, although this process was felt to be both mathematically robust and intuitively correct, it was felt to be a rather complicated and cumbersome exercise. Of more significance however, it was not clear how such a target profile could be translated into engineering specification requirements. For example, what would be the changes to the design detail required to change a Spirited rating from 7.5 to 8.5. The use of the Sound Quality Profile to define a subjective Sound Quality target could therefore not be easily incorporated within a Sound Quality Engineering Process that could be used to drive the vehicle development process.

The second concern was the level of redundancy within the Sound Quality Profile. The twelve semantics had been selected such that both the refinement aspects and the performance aspects of Sound Quality could be accounted for within the upper and lower halves of the profile respectively. However, the use of all twelve of the semantics has introduced an element of redundancy. For example it is difficult to describe the differences between each of the semantics Spirited, Fun and Exciting, as it is just as difficult to describe the difference between Quiet and Refined. An analysis of the confidence limit bands around the average scores for these semantics was conducted, and it was established that there was not a statistically significant difference between these groups, and also other groups of semantics. Consequently, the use of twelve semantics within the Profile was over-determining the characterisation of Sound Quality, and as a result any target based on this Profile would be unnecessarily over determined and complicated.

The third concern with the profile was that although it provided a means of characterising the Sound Quality, the link between the profile and the delivery of the Jaguar core-mark value of Refined Power was not clear. It was previously outlined that a means of measuring the degree of achievement in Refined Power was one of the requirements of the Sound Quality Engineering Process. A target Sound Quality profile would not provide a measure of this degree of achievement.

The concerns with the proposed means of using the Sound Quality Profile to set subjective Sound Quality targets, the inability of such a target to drive the vehicle development process, the level of redundancy in the profile, and the inability to relate the profile to the Jaguar core-mark value of Refined Power, all indicated that although the profile provided a good means for quantifying Sound Quality, it did not provide a good means of setting Sound Quality targets. These concerns initiated the next significant work package within the EngD research programme. This work package was aimed at simplifying the characterisation of Sound Quality, and developing an alternative means of setting subjective Sound Quality Targets that would support the delivery of the core-mark value of Refined Power and that could be used to drive the vehicle development process.

6.3.6 Simplification of Sound Quality Characterisation

The first concern that needed to be addressed was the level of redundancy in the Sound Quality Profile. A study was therefore initiated into establishing a means of simplifying the characterisation of Sound Quality. The semantic differential evaluation technique had been in use by the VAG process over a considerable period of time, and during this time Sound Quality profiles had been established for a total of 72 different vehicles. These profiles were established for each of the vehicles in Jaguar's product portfolio, and for all of the competitors within each of these vehicle segments. This resulted in an extensive database of Sound Quality profiles. This database was analysed to establish if an alternative and simpler means of characterising the nature of the differences in the Sound Quality character between all of these vehicles could be developed.

A number of different techniques were applied in this analysis. These included a detailed examination of the correlation levels between the twelve semantics of the profile to establish the presence of any structure in the dataset, and the use of cluster analysis to empirically classify the twelve semantics into groups or clusters. These analysis techniques indicated that there was a significant degree of structure to the dataset, and that the characterisation of Sound Quality could be reduced to a smaller number of dimensions that accounted for the Sound Quality ratings of groups or clusters of semantics. However, although these analyses had indicated that the complexity of the twelve semantics of the Sound Quality characterisation could be reduced they did not identify the underlying nature of the variability within the dataset.

One of the most significant findings from the review of the previously published literature was the work by a number of different researchers that used the results of semantic differential appraisals to identify the subjective nature of Sound Quality in terms of a number of underlying factors. These researchers had used either Factor Analysis or Principal Component Analysis to identify these underlying factors. However, the earlier review of this previous research outlined that their work would only ever have identified the underlying nature of Sound Quality for pre-recorded sound stimuli replayed to jury subjects over headphones in an artificial laboratory environment. As their analyses were not based upon the assessment of the Sound Quality from actual drive appraisals it was felt they did not identify the underlying nature of the Sound Quality as perceived by the customer. The VAG semantic differential appraisal results however, were based upon actual drive appraisals. It was decided therefore to use Principal Component Analysis on the VAG semantic differential ratings database to establish the nature of the variability in the dataset and to establish if it would be possible to reduce the characterisation of Sound Quality to a smaller number of underlying dimensions. The application of Principal Component Analysis to the results of the VAG semantic differential Sound Quality assessments is detailed in the submission to the EngD portfolio titled *Sound Quality Brand Engineering* [25]. The key findings from this analysis are outlined in the following sections.

6.3.6.1 Number and Nature of the Underlying Dimensions of Sound Quality.

It was mentioned previously that the most important aspect of Principal Component Analysis is the ability to correctly interpret the results of the analysis. This is necessary to confirm that the results are representing the true nature of the variability in the dataset and not merely representing mathematical noise. The first result of the Principal Component Analysis that needs to be examined is the identified dimensionality. This is the number of the underlying dimensions or principal components identified in the dataset. The best way of examining this is through the Scree plot, illustrated in Figure 10. The Scree plot provides a measure of the level of the variation accounted for by each of the underlying principal components established from the analysis.

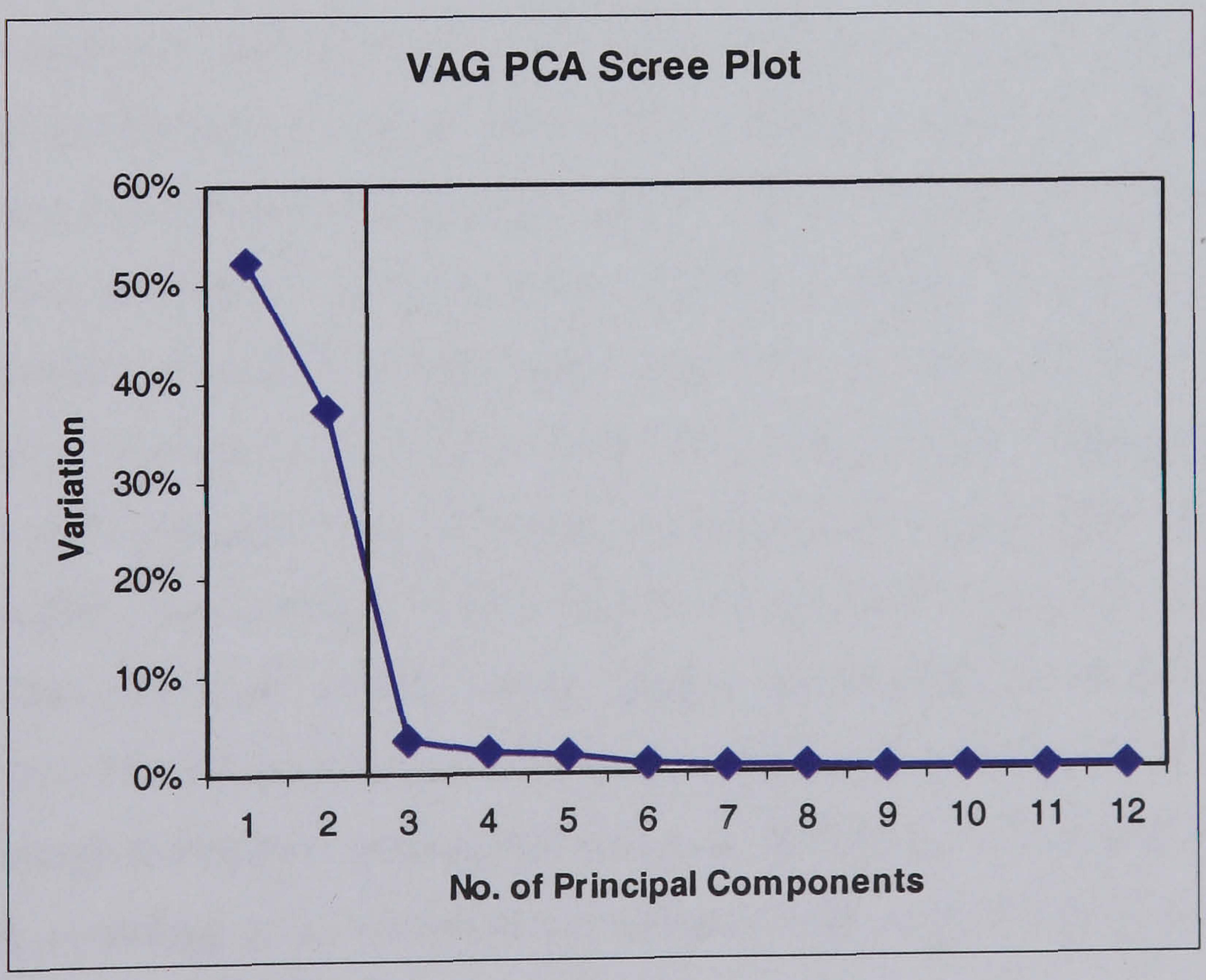


Figure 10: Principal Component Analysis Scree Plot

It is an accepted general rule of thumb, see Kim [7], that the significant 'knee' on the Scree plot represents the point at which the mathematically derived principal components are merely representing random variation, and that the number of principal components to the left of this knee can be taken to represent the real structure in the dataset. In Figure 10, there is a significant knee between the second and third principal components, and consequently it may be concluded that the nature of the variability in the dataset can be reduced to two underlying dimensions. These two underlying dimensions account for 53% and 36% of the variation in the dataset. Together they account for 89% of the total variation. The remaining 11% is merely representing random variation. Other tests were conducted on the dimensionality comparing the level of variation accounted for by each principal component against the expected level of variation and again it was confirmed that there are only two underlying dimensions to the dataset. The Principal Component Analysis applied to the VAG semantic differential appraisal results had therefore confirmed that the nature of the Sound Quality characterisation could be reduced to two underlying dimensions or Principal Components. This was the first significant conclusion from the analysis.

The next step in the analysis was to interpret the results in order to add meaning to the two underlying dimensions. This was achieved by comparing the level of correlation between the initial semantic variables and the derived principal components. The levels of correlation are listed in Appendix B. The first part of this analysis involved checking for statistically significant degrees of correlation. This analysis established that each of the semantics Powerful, Sporty, Exciting, Fun and Spirited were significantly correlated with the first principal component and that there was no evidence of any level of correlation between these semantics and the second principal component. Similarly it was also established that each of the semantics Comfortable, Quiet and Refined were significantly correlated with the second principal component and that there was no evidence of any level of correlation between these semantics and the first principal component. This analysis indicated that the first principal component was accounting for the variation in the performance related Sound Quality characteristics, whilst the second principal component was accounting for the variation in the refinement related Sound Quality characteristics. An alternative means of comparing the levels of correlation between the initial semantic variables and the derived principal components is through the Factor Loading Plot illustrated in Figure 11. This plot locates each input semantic variable according to its correlation coefficient with each of the principal components, represented by the axes of the plot.

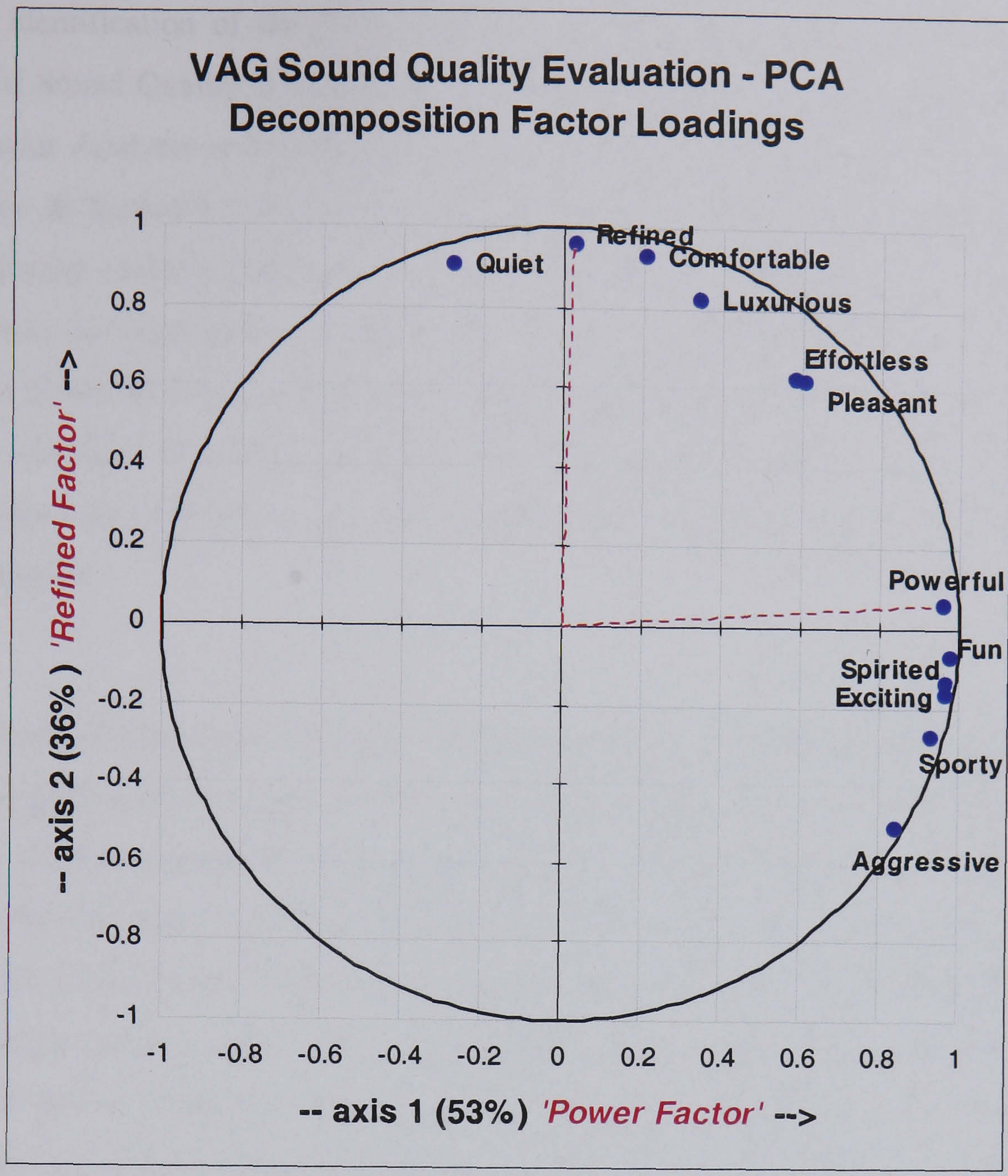


Figure 11: Principal Component Analysis Factor Loading Plot

The Factor Loading Plot illustrates that the Powerful semantic has the greatest degree of correlation with the First Principle Component, whilst at the same time the lowest degree of correlation with the Second Principal Component. Similarly the Refined semantic has the greatest degree of correlation with the Second Principal Component, while at the same time the lowest degree of correlation with the First Principal Component. The Powerful and Refined semantics have therefore been established as the orthogonal semantics that most closely correlate with the First and Second Principal Components. These correlations have added meaning to the two underlying dimensions of Sound Quality. They have demonstrated that the characterisation of Sound Quality can be reduced to the two underlying dimensions referred to as the *Power Factor* and the *Refined Factor*. Collectively they are referred to as the two Underlying Dimensions of Sound Quality. This was the second significant conclusion from the analysis.

The identification of the *Power Factor* and the *Refined Factor* as the two underlying dimensions of Sound Quality is consistent with the findings of the previous researchers who had also used Factor Analysis or Principal Component Analysis to examine the underlying nature of Sound Quality. In Section 5.1, the summary of this previous research had outlined that the nature of the Sound Quality could be represented by two, and in some case three, underlying dimensions. The first of these two dimensions was a strength or power related factor. This is consistent with the *Power Factor* identified from the Principal Component Analysis of the VAG results. The second of these was a comfort related factor. This is consistent with the *Refined Factor* identified. The Principal Component Analysis of the VAG results did not identify a third significant underlying factor or dimension.

The level of correlation between the initial Pleasant / Annoying semantic pair and each of the Power and Refined dimensions is significant. It had previously been outlined that the ratings for the Pleasant / Annoying semantic pair had provided a measure of the preference for Sound Quality expressed by the customers. The Factor Loading Plot in Figure 11 illustrates both the level and the direction of the correlation between the Pleasant semantic and the two principal factors. It was found to correlate equally with both of the underlying dimensions. This implies that the overall preference for Sound Quality is based upon the delivery of high levels of both the Power and Refined Factors, or rather a balanced delivery of both. This balance between the delivery of both dimensions of Sound Quality formed the basis of the subjective Sound Quality target setting process that is detailed later in Section 6.3.7

The significant improvement that the Principal Component Analysis applied to the VAG results has made over the previous research is that the identified underlying dimensions were based upon actual drive appraisals, and not just jury listening tests. The underlying dimensions are therefore more representative of what the customer experiences. In addition the Principal Component Analysis was based upon the largest set of vehicles yet processed. The largest number of vehicles previously analysed were by Bisping [22] who based his analysis on 51 sound recordings, and by Hashimoto [19] who based his analysis on 36 sound recordings. All of the other papers reviewed were based on the analysis of between 5 and 11 sound recordings. When compared to the 72 vehicles used in this analysis, it can be seen to be the most comprehensive review of Sound Quality yet conducted. Of added significance however, all of the vehicles evaluated by the VAG team were either premium luxury saloons or sports cars, fitted with I6, V6, V8 or V12 engine configurations. None of the other studies were based solely on these premium luxury vehicles. This study can therefore be seen to be the most comprehensive review of the nature of Sound Quality within the premium luxury saloon and sports car vehicle segments.

It is worth noting that the ability to quantify the nature of Sound Quality according to the two dimensions of Powerfulness and Refinement, is purely coincidental with the Jaguar core-mark value of Refined Power. It has however provided a clear link between this core-mark value and the characterisation of Sound Quality that had not been achieved through the Sound Quality Profile. The Principal Component Analysis has therefore, for the first time, provided a means of relating the delivery of Sound Quality to the delivery of the core-mark value of Refined Power. This was felt to be a significant breakthrough in the research.

6.3.6.2 2-Dimensional Sound Quality Space

The identification of the two Underlying Dimensions of Sound Quality as a Power Factor and a Refined Factor implied that measures of these two Underlying Dimensions could be used to quantify the Sound Quality character for a given vehicle. The principal component analysis provided a means of illustrating this character. Mathematically the principal components or underlying dimensions are derived from linear combinations of the initial input variables. For example PC1 = m1.Pleasant + n1.Powerful + ... + x1.Refined, where m1 -> x1 are weighting factors for the First Principal Component. Similarly PC2 = m2.Pleasant + ... + x2.Refined. It is possible to calculate a single factor score for each vehicle using that factor's weighted combination of the initial semantic variable ratings. Using this approach a Power Factor score and a Refined Factor score can be calculated for each of the vehicles evaluated. These Power Factor Scores and Refined Factor Scores can then be plotted against each other within what is referred to as a Factor Score Plot. The Factor Score Plot established from the Principal Component Analysis for the first and second principal components, is illustrated in Figure 12. This plot locates each of the vehicles evaluated by the VAG process within a 2-Dimensional Space, the axes of which are defined by each of the Power and Refined Factors. This is referred to as the 2-Dimensional (2D) Sound Quality Space. It provides the same information about the Sound Quality character for each vehicle that had previously been provided in the Sound Quality Profile. However, within the 2D Sound Quality Space this character is expressed only in terms of each of the underlying dimensions of Sound Quality. This has eliminated the redundancy associated with the use of the twelve semantics in the Sound Quality profile.

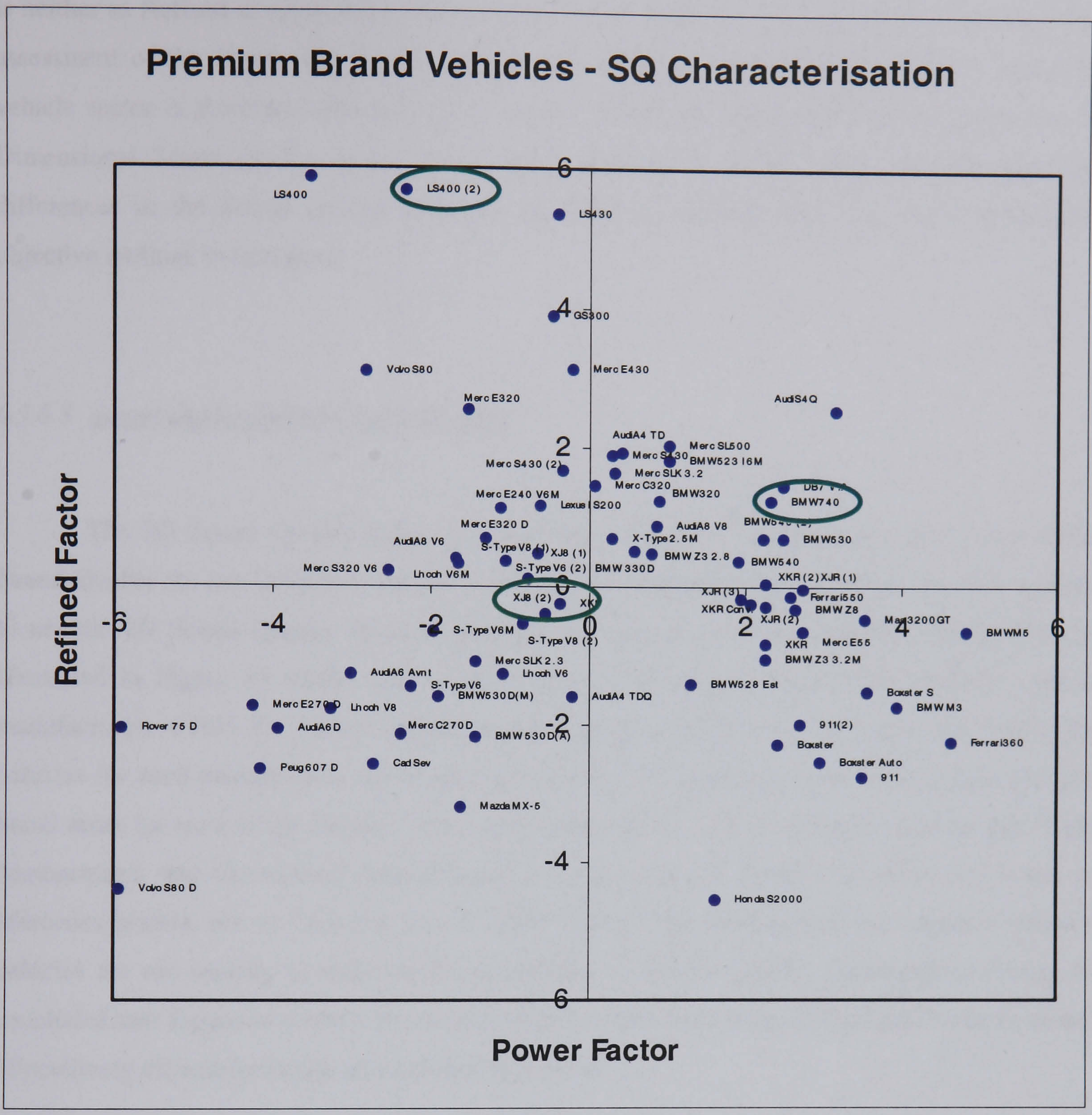


Figure 12: Principal Component Analysis Factor Score Plot – 2-Dimensional SQ Space

The location of the different vehicles within the 2-Dimensional Sound Quality Space can be used to quantify their Sound Quality characters. The Lexus LS400, highlighted in Figure 12, was evaluated to be the most Refined of all the 72 vehicles assessed, but it was not evaluated to have a high Powerful character. The BMW740, also highlighted, was evaluated to have a much more Powerful Sound Quality character, and although less Refined than the Lexus LS400, its location in the upper right hand quadrant of the 2D Sound Quality space, resulted in it being identified as the vehicle with the most preferred overall Sound Quality character. This reflects the direction of correlation for the Pleasant semantic illustrated in the Factor Loading Plot in Figure 11. The location of the Jaguar XJ8 within the 2D Sound Quality Space, however, illustrates that it is neither as Refined as either the Lexus and the BMW740, nor as Powerful as the BMW740. The assessment of the Jaguar XJ8 as the vehicle with the least preferred Sound Quality within its vehicle sector is therefore reflected by its location within the 2D Sound Quality space. The 2-Dimensional Sound Quality Space has therefore provided a simple means of quantifying the differences in the Sound Quality character of different vehicles. This was the first research objective outlined in Section 4.

6.3.6.3 *Sound Quality Brand Characterisation*

The 2D Sound Quality Space has provided a means of characterising the nature of the Sound Quality for any individual vehicle. In addition to these individual vehicles it is also possible to use the 2D Sound Quality Space to quantify the differences between vehicle brands. This is illustrated in Figure 13 where each of the vehicles belonging to each of the different vehicle manufacturers within the luxury vehicle sectors has been identified. The space over which the vehicles for each manufacturer are located is outlined. This approach has identified characteristic brand areas for each of the Jaguar, Lexus, Mercedes, BMW, Audi and Lincoln core brands. It has demonstrated that the existing Jaguar brand area is neither as Refined as either the Lexus or Mercedes brands, nor as Powerful as the BMW brand. This demonstrates that Jaguar's existing vehicles are not leading in either of the dimensions of Sound Quality. Consequently it may be concluded that Jaguar as a brand is not delivering its core-mark value of Refined Power as means of positively differentiating itself from the competition.

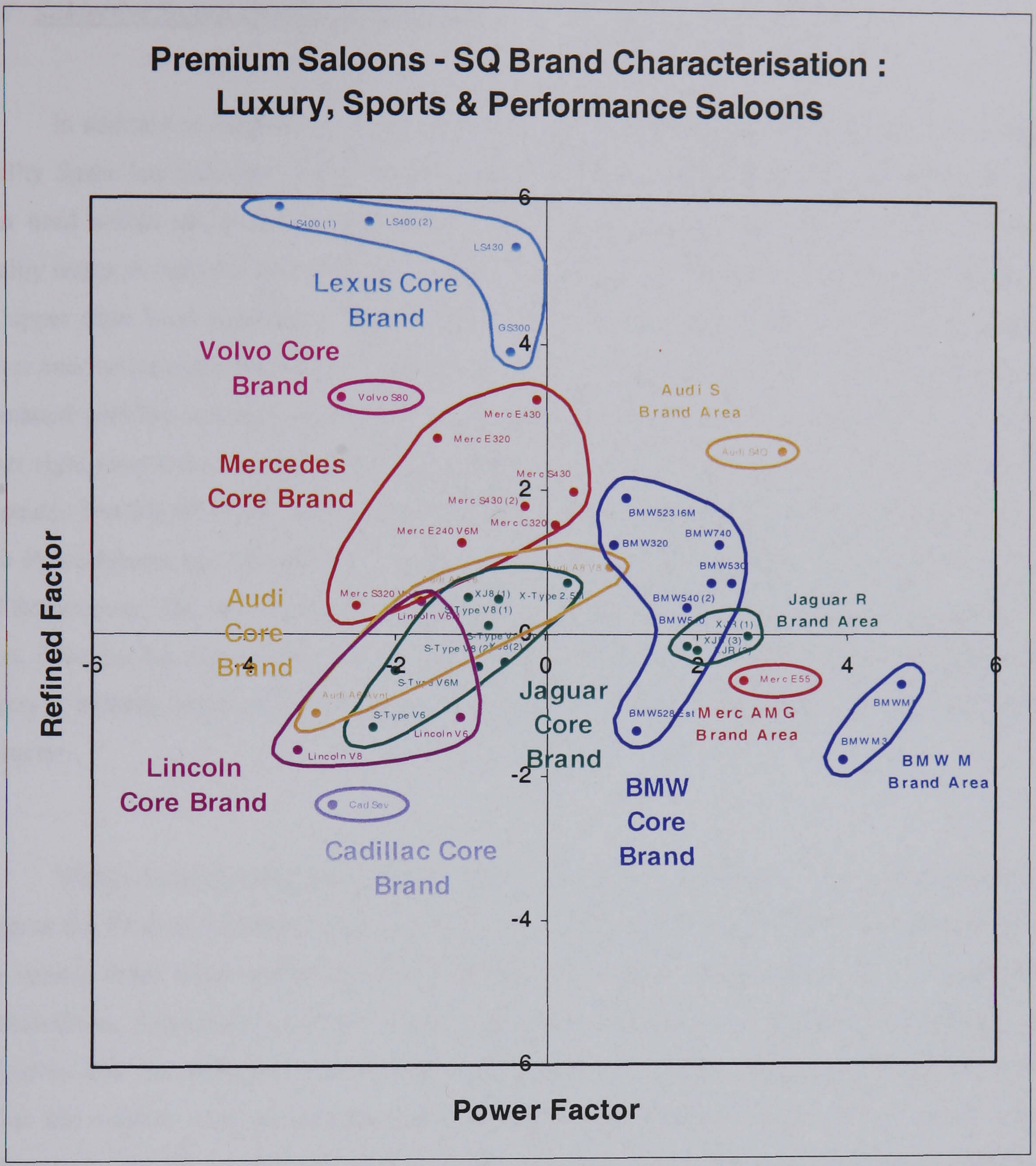


Figure 13: Premium Saloons Sound Quality Brand Characterisation

6.3.7 Subjective Sound Quality Target Setting

In addition to simplifying the characterisation of Sound Quality, the 2-Dimensional Sound Quality Space has provided a more robust means of targeting Sound Quality than had previously been used within the Sound Quality Profile. This new process for setting a subjective Sound Quality target is outlined in this section. It had previously been mentioned that vehicles located in the upper right hand quadrant of the 2D Space were those that had a balanced delivery of both Power and Refinement. This balance delivered a Pleasant Sound Quality character that was directly correlated with the customer preferences for Sound Quality. Consequently a vehicle located in the upper right hand corner would deliver the optimum Sound Quality character. However, Figure 12 illustrates that for all of the 72 vehicles assessed no vehicle has been found to have high levels of both Powerfulness and Refinement. There is in effect a trade-off between the delivery of Power and Refinement. The more Powerful a sound is then the less Refined it is perceived to be, and vice versa. This implies that when it comes to using the 2D Sound Quality Space to set Sound Quality targets a balance must be struck between the delivery of a Powerful character and a Refined character.

Within the target setting process at Jaguar there is a requirement to relate any vehicle level target to the Product Attribute Leadership Strategy, or PALS, process. The PALS process classifies any vehicle level target according to five different categories. These categories are Leadership, Best-in-Class, Amongst-the-Leaders, Competitive and Uncompetitive. Appendix C outlines the definition and the difference between these five categories. Effectively the different categories define the vehicle level performances that can be perceived by the customer to provide clear differentials between competing vehicles. It was necessary to translate these five PALS categories to the 2D Sound Quality Space if it was to be used to define the vehicle level targets. This was achieved by defining a series of contour lines, centred around the upper right hand corner of the 2D Space. Figure 14 illustrates these contour lines along with the location of only the vehicles competing in the large luxury vehicle vector, including the Jaguar XJ8, Lexus LS400 and BMW740. The contour lines were used to define the transitions between the five PALS categories. The use of these contours is based upon the principle that vehicles with the most preferred Sound Quality are located in the upper right hand corner of the 2D Sound Quality Space. This defines the location of vehicles with Leadership in Sound Quality. As the levels of both Refinement and Powerfulness are reduced, the overall Sound Quality performance moves from Leadership to Best-in-Class to Amongst-the-Leaders to Competitive and finally Uncompetitive. The spacing between the contours has been based upon the confidence levels established for the vehicles within the 2D Space. It has been established through an analysis of the variability of the results that the confidence levels around each vehicle is 2 Factor Scores in each dimension. The submission to the EngD portfolio titled *Subjective Sound Quality Target Setting* [4] details this analysis. This implies that the difference in the Sound Quality between vehicles can be regarded as significant if the difference between their locations within the 2D Sound Quality Space is greater than two factor scores. The requirement of the PALS process is to define differences between the categories that can be perceived by the customer. Consequently the indicated difference of two factor scores between the contour lines has defined the differences between the PALS categories.

Figure 14 illustrates the location of the contours that define the different PALS category regions for the large luxury vehicle competitor set. With the centre of the contours at the top right hand corner the vehicle that meets the increasing contour lines first is the BMW740. This is the leading competitor for Sound Quality within this vehicle sector. This is consistent with each of the previous customer evaluations, internal jury listening studies and the VAG ratings for the Pleasant semantic However, as both the Mercedes S430 and the Audi A8 were within 2 Factor Scores of the BMW740, the BMW740 was not found to be displaying Leadership performance as defend by the PALS process, see Appendix C, but rather Best-in-Class performance. The BMW740 therefore defines the location of the Best-in-Class contour line. Inside this contour line, towards the upper right hand corner defines the Best-in-Class target region, and the 2 Factor Score differential defines the location of each of the other four PALS category regions. Through the mapping of the PALS regions within the 2D Sound Quality Space it is possible to relate the vehicle level performance for each of the existing vehicles to each of the these PALS categories. The BMW740, as previously mentioned, is the Best-in-Class leader. The Mercedes S430 and the Audi A8 are in the Amongst-the-Leaders region. The old Lexus LS400 vehicles were evaluated to be only competitive for overall Sound Quality, despite the high Refined Factor scores. The existing Jaguar XJ8 vehicles that were evaluated both fall within the Competitive region. This process has therefore provided a means of quantifying the delivery of Sound Quality in terms of the PALS categories, and has demonstrated that the existing Jaguar XJ8 is only delivering competitive levels of Sound Quality.

The next step involved using the PALS category regions within the 2D Sound Quality Space to define the Sound Quality target for the new X350 vehicle programme. The PALS target for the Powertrain Sound Quality defined by the Vehicle Programme team and the Marketing Organisation was to be Best-in-Class. Anywhere within the Best-in-Class region would deliver this

Best-in-Class target. It was decided by the Vehicle Programme Team that the Sound Quality character for the new X350 should not be as Refined and Quiet as the Lexus LS400/430, nor as Powerful and Aggressive as the BMW740, but should rather deliver a better balance between the Refinement levels and the Powerful character. Consequently the region highlighted in Figure 14 was defined as the Brand Target Area for the new X350 vehicle, the next XJ8. The location of this target area defined the transition within the 2D Space required to move the existing XJ8 to the target area. This transition identified the required improvements to each of the Powerful and Refined dimensions of Sound Quality. The new X350 would need to enhance both the Refinement levels and Powerful sound character of the existing XJ8 in order to deliver the new target.

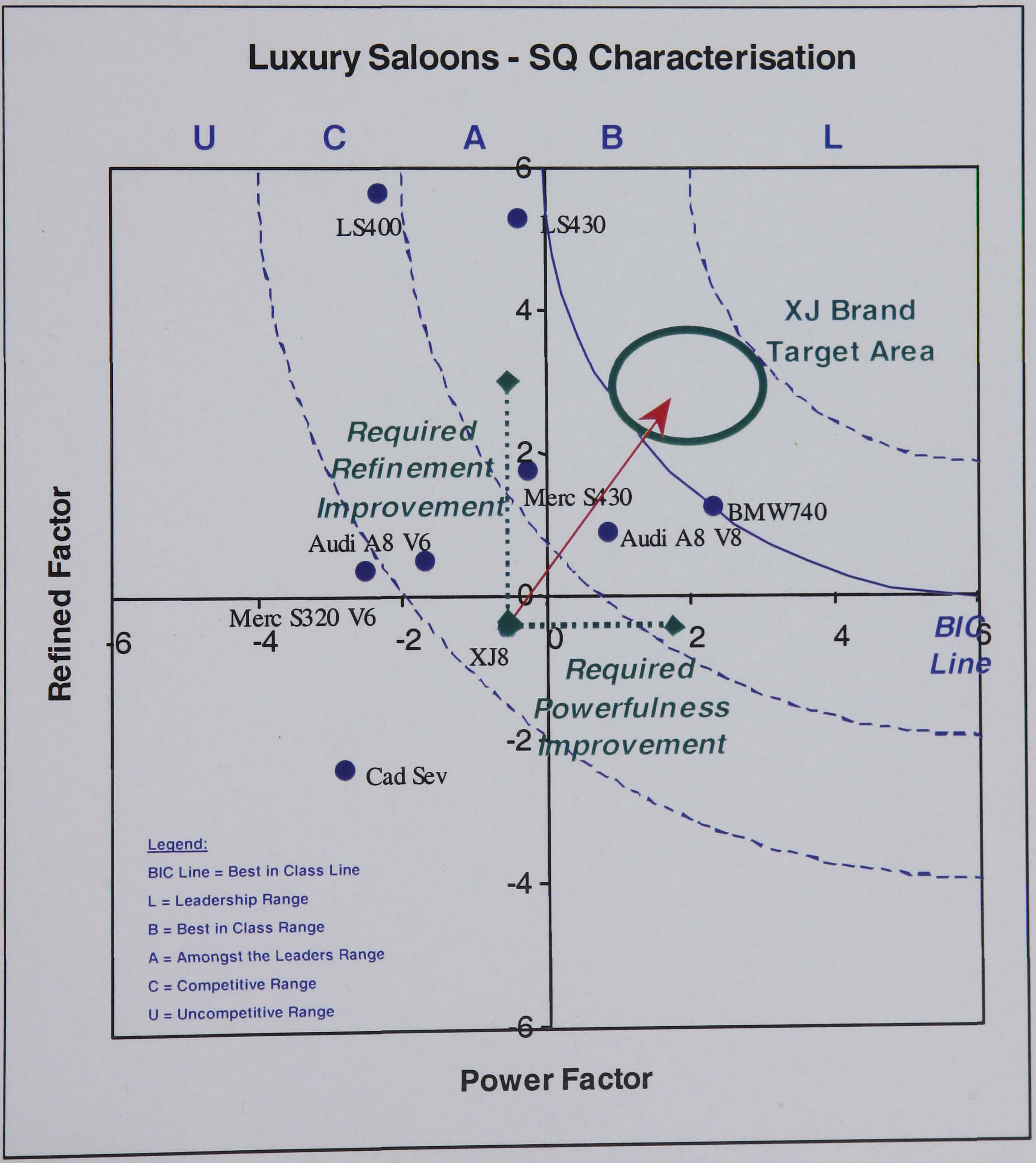


Figure 14: XJ Series Subjective Sound Quality Target

The use of the 2 Dimensional Sound Quality Space to define the subjective Sound Quality target has provided a key breakthrough within the target setting process. It has provided the means of translating the vehicle programme PALS target to a subjective Sound Quality target expressed in terms of the improvements required to deliver each of the elements of the Refined Power core-mark value. This had been the second research objective outlined in Section 4.

6.3.8 Jaguar Brand Sound Quality Target

Since the pilot application of the subjective Sound Quality target setting process on the X350 programme the process of defining Sound Quality targets has been applied to each of the other vehicles in Jaguar's product portfolio. For each of the S-Type, X-Type and XK-Type vehicle programmes, and for the performance R-Brand versions of each of these derivatives the target areas within the 2-Dimensional Sound Quality Space relative to each of their competitor vehicle sets have been defined. Figure 15 illustrates the combined target area for all of these vehicle programmes. This area defines the future Jaguar Brand Sound Quality characteristics. The target is to deliver the Refinement levels of the Mercedes brand and the Powerful sound character levels of the BMW brand. The delivery of vehicles with Sound Quality characters that locate within this brand target area would support the use of the Jaguar core-mark value of Refined Power as a means of positively differentiating its products from the competition.

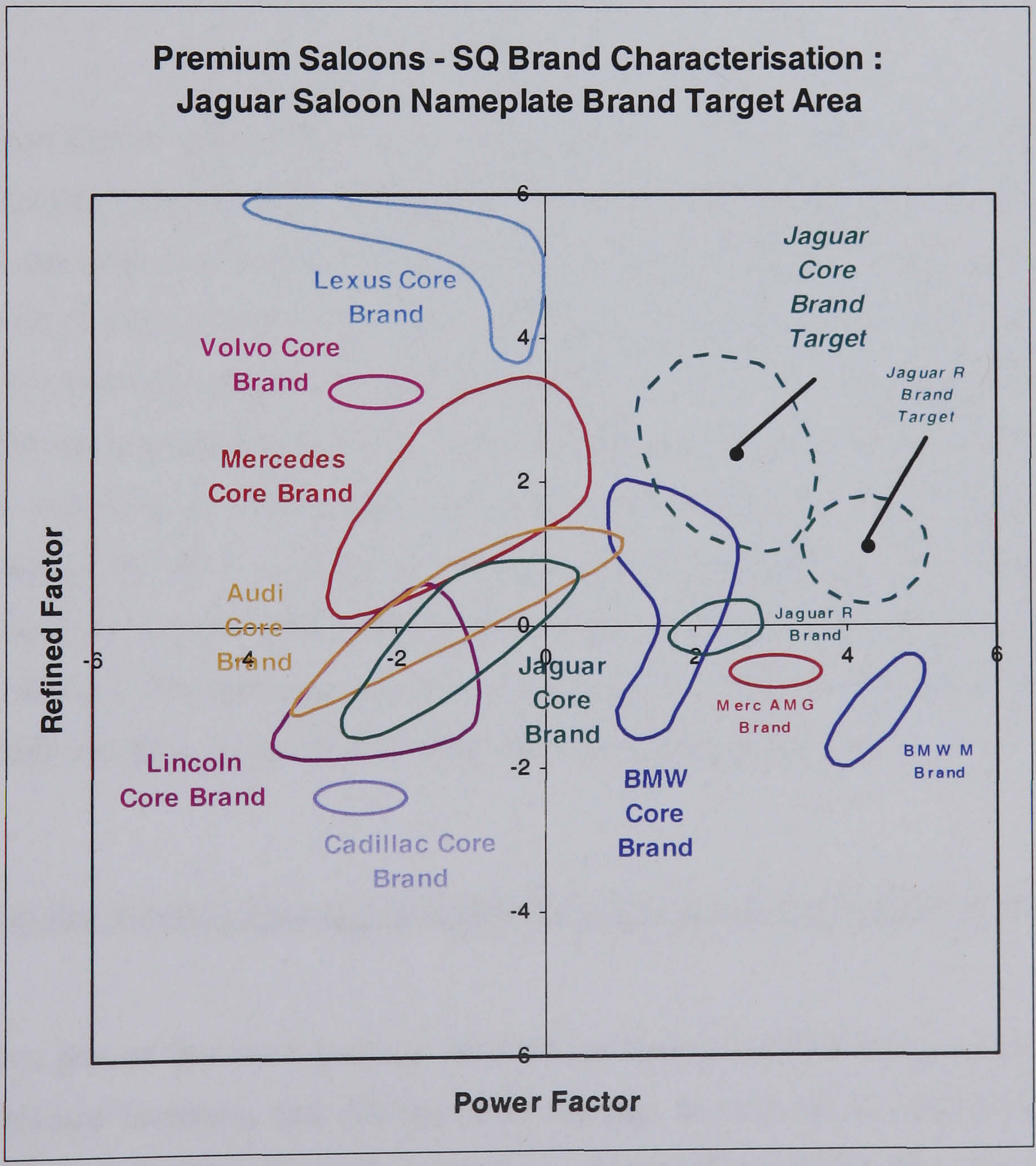


Figure 15: Jaguar Brand Subjective Sound Quality Target

6.4 Understanding the Sounds - Identification of Key Acoustic Features

The previous sections have outlined the EngD research work that was focussed on delivering the first element of the Sound Quality Engineering Process, *Understanding the Requirements of the Sounds.* This involved developing a process for quantifying the subjective nature of the Sound Quality of different vehicles and then developing a system to subjectively target the Sound Quality to support the delivery of the individual vehicle programme requirements and the Jaguar brand's core-mark value of Refined Power. It was necessary to ensure that this target setting process captured the subjective nature of Sound Quality as perceived by the customer, and as a result this step in the Sound Quality Engineering Process was intentionally kept subjective in nature. However, in order to incorporate this subjective target within the vehicle development process it is necessary to translate this subjective target into objective vehicle level requirements that can be used to drive the design process.

The first part of this translation is captured in the second step of the Sound Quality Engineering Process, *Understanding the Sounds.* The 2D Sound Quality Space in Figure 14 was used to define the subjective Sound Quality target for the new X350 vehicle programme. It also defined the level of improvement required to each of the dimensions of Sound Quality over the existing XJ8. To deliver these required improvements it is necessary to understand the reasons why the existing XJ8 was evaluated to have low ratings for each of the Power and the Refined Factors. This involved examining the sound signature of the XJ8 vehicle and identifying the acoustic features responsible for the low ratings for each of the dimensions of Sound Quality. A work package was therefore defined within the EngD research programme with the aim of identifying these acoustic features. The principal objective of this research was to identify the reasons why the XJ8 sounded both less Refined and less Powerful than the leading competitors.

6.4.1 Review of Key Acoustic Features Identified from Previous Sound Quality Research

The first part of this work package involved reviewing the findings established from the previously published literature, and relating these findings to each of the identified underlying dimensions of Sound Quality. Table 2 in Section 5.2 related the seven key acoustic features identified from the previous research to each of the Comfort or Refined and Strength or Powerful dimensions of Sound Quality. The review of this literature identified that six of these acoustic features would need to be compared with the sound signatures of the XJ8 and it's competitors. These six acoustic features were the Loudness Level, the Sharpness Level, the Linearity, the Level of the Engine Firing order, the Level of the Low Engine Orders and the Level of Roughness or Rumble. The following sections summarise the key findings that were established.

6.4.1.1 *Standard Metrics – Loudness, Sharpness, Roughness & Linearity*

The first part of the process involved comparing the Loudness, Sharpness & Roughness levels between the XJ8 and its competitors and also comparing the Linearity or change in the Loudness or Sound Pressure Level between the vehicles. Each of these metrics were calculated from the measured sound recordings in each of the vehicles in the large luxury vehicle sector, including the Jaguar XJ8 and the identified class-leader, the BMW740. These values were compared with the subjective ratings established from the jury listening studies and from the VAG appraisals to identify which of these standard metrics accounted for the differences in either of the dimensions of Sound Quality. This comparison identified that the Loudness level and the Sharpness level were the two most significant of the metrics previously identified as important from the literature review. The XJ8 was found to be significantly Louder and Sharper than the competition. The difference between the XJ8 and the class-leading BMW740 for each of these two metrics is illustrated in Figure 16.

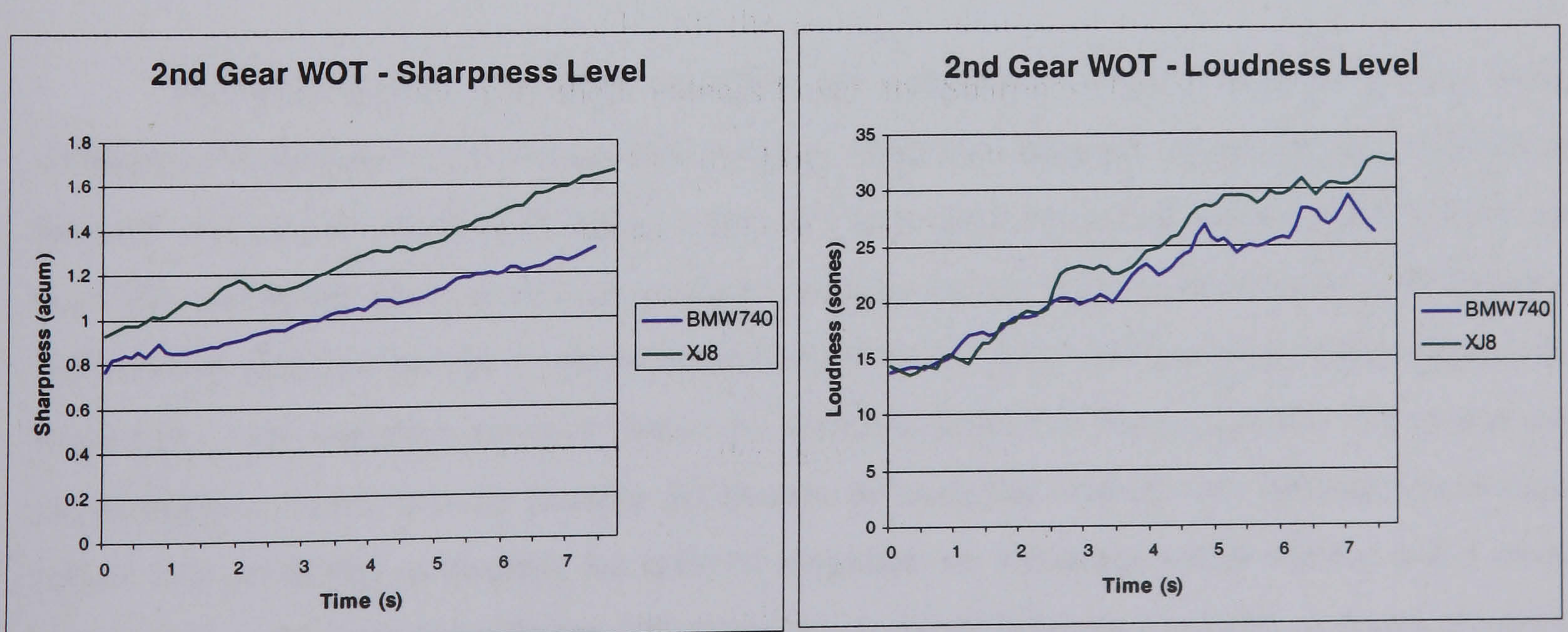


Figure 16: Loudness and Sharpness Metric Comparison - BMW740 vs. XJ8

Both the jury studies and the VAG appraisals had indicated that the XJ8 was significantly less Refined than the competition. The increased levels of Loudness and Sharpness on the XJ8 reflect this low level of Refinement. This is consistent with the findings from the literature review, which had identified Loudness and Sharpness as two of the key acoustic features responsible for the comfort or Refined related aspects of Sound Quality. The Sharpness metric in particular was found to provide a good measure of the difference in Refinement between the vehicles. Sharpness provides a measure of the high frequency content in a sound, and consequently the high levels of sharpness on the XJ8 suggested that the reason for the low levels of Refinement on the XJ8 was the presence of excessive levels of high frequency engine noise. These high levels of high frequency engine noise would also account for the increased Loudness level of the XJ8, and consequently the Loudness level could also bee seen to provide a good measure of the Refinement aspects of Sound Quality.

The previously reported findings from the literature review, had related an increase in Loudness to both a reduction in the perception of Refinement and to an increase in the perception of Powerfulness, see Table 2. However, the increased level of Loudness on the XJ8 did not make it sound more Powerful than competitors such as the BMW740. On the contrary, despite the BMW740 being Quieter than the XJ8, it was perceived to be significantly more Powerful. Consequently, the previously reported findings from the literature review, which had related an increase in Loudness to an increased perception of Powerfulness, was found not to apply to the sounds from the XJ8 and its competitors.

The other metrics evaluated, Linearity and Roughness, failed to account for any of the differences in Sound Quality between the vehicles. However, although the Roughness metric itself failed to account for these differences it was felt that the level of the engine order rumble that generates the roughness was still a significant acoustic feature that could be used to differentiate between the vehicles. Indeed it will be illustrated in Section 6.4.2 that the level of the engine order rumble is a very important acoustic feature for both dimensions of Sound Quality. The reason why the Roughness metric did not identify differences between the vehicles was because the standard metric was developed to quantify the level of roughness on stationary sound signals, and it would appear that it does not quantify the difference in roughness between transient, or speed changing, sound signals. The 2nd Gear Wide Open Throttle sound recordings used for the comparisons were such transient sound signals.

6.4.1.2 Engine Order Analysis – Colour Maps

The remaining key acoustic features identified from the literature review were the Level of Engine Firing Order and the Level of the Low Engine Orders. The Level of Engine Firing Order had previously been related to the Powerful dimension of Sound Quality, whilst the Level of the Low Engine Orders had been related to both the Refined and the Powerful dimensions of Sound Quality. The comparison of both of these acoustic features requires an analysis of the distribution in the engine order content over the operating speed of the engine. It is assumed that the reader has a basic knowledge of engine orders and harmonic patterns prior to reading this section. In the following section a numeric value followed by the letter E is used to denote the different engine orders, e.g. 4E represents the fourth engine order. The best way of illustrating the engine order distribution over the operating speed of the engine is through a Colour Map. The Colour Maps for both the Jaguar XJ8 and the BMW740 undergoing a 2GWOT acceleration are illustrated in Figure 17. The x-axis of the Colour Map represents time. It could alternatively represent engine rpm. It illustrates the change in character of the engine sound over the full operating speed of the engine as the vehicle undergoes the 2GWOT acceleration. The y-axis represents frequency. For the two vehicles displayed the majority of the significant engine sound occurs below 2 kHz, so in Figure 17, the frequency is displayed from 0 to 2 kHz. The lines in the Colour Map represent the individual engine orders increasing in frequency as the engine speed increases. The amplitude of these engine orders is represented by the colour variation indicated by the legend.

The two colour maps from the XJ8 and the BMW740 were compared to identify the acoustic features that were responsible for the differences between them. The first comparison that was made was the difference in the level of the Engine Firing Orders. It was established that the level of the 4E firing order from the V8 engine in the XJ8 was higher than the level of the 4E firing order on the BMW740. The literature review had suggested that higher levels of the firing order would increase the perception of Powerfulness. However, as the BMW740 was subjectively rated to be more Powerful than the XJ8, the higher levels of 4E on the XJ8 were not contributing to an increased perception of Powerfulness. Consequently it may be concluded that in contrast to the previous findings established from the literature review higher levels of the firing order 4E are not responsible for increasing the perception of Powerfulness for this set of vehicles.

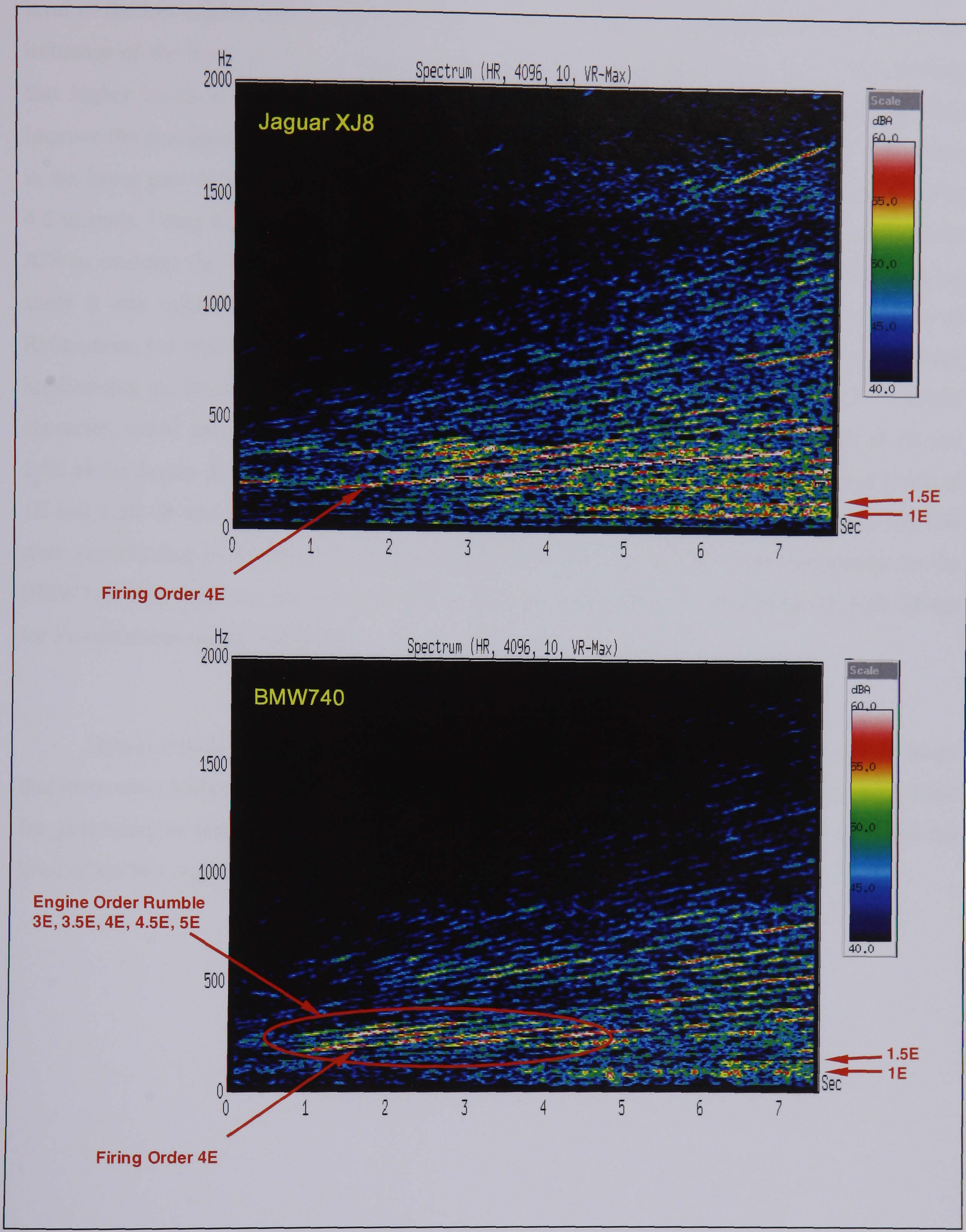


Figure 17: Jaguar XJ8 vs. BMW740 Colour Maps

The other acoustic feature identified to be important from the literature review was the level of the low engine orders. There was disagreement amongst the previous researchers over the influence of the level of the low engine orders on the subjective perception, with some claiming that higher levels of these orders degrade the Refinement level, and others claiming that they improve the perception of the Powerful character. In Figure 17 the levels of the 1E and 1.5E orders in the lower part of the colour maps are higher in the XJ8 than in the BMW740, particularly after 4.5 seconds. Using digital filtering techniques these orders were removed from the recording of the XJ8 to evaluate the effect of their removal on the subjective perception. Using a jury listening study it was established that these 1E and 1.5E orders were not degrading the perception of Refinement, but when they were removed the perception of Powerfulness was degraded. This study implied that the levels of the 1E and the 1.5E on the XJ8 were contributing towards its Powerful character, rather than degrading its Refinement character. However, the higher levels of 1E and 1.5E on the Jaguar XJ8 did not make it sound as Powerful as the BMW740, that had lower levels of 1E and 1.5E. It was concluded therefore that the presence of the 1E and 1.5E orders on the XJ8 were contributing to its Powerful Sound Quality character, but as they were not present on the BMW740, they were not the acoustic feature that was responsible for delivering the high ratings for Powerfulness on the BMW740.

It was concluded form the comparison of the Engine Order Analysis and the Colour Maps that there was another acoustic feature in the sound signature of the BMW740 that was responsible for generating its high levels of perceived Powerfulness, other than the firing order level and the level of the low engine orders. This acoustic feature would need to be identified.

6.4.2 *Trade-Off Effect of Engine Order Rumble on the Powerful & Refinement Dimensions*

It was mentioned in Section 6.4.1.1 that the Roughness metric did not provide a measure of the differences between the Sound Quality of the different vehicles. However, this was believed to be because the roughness metric was not suitable for analysing transient or accelerating sounds. Consequently the roughness generated by the engine order rumble could still have been a significant acoustic feature. The literature review had indicated that Roughness or Rumble was a key acoustic feature in the perception of Sound Quality, and that it was found to affect both the Refinement and the Powerful aspects of Sound Quality. Therefore, a further study was initiated to establish if Rumble was the key acoustic feature responsible for the high subjective Powerful ratings of the BMW740.

The Colour Map of the BMW740 illustrated in Figure 17, shows that there is a cluster of engine orders, 3E, 3.5E, 4E, 4.5E and 5E, in a frequency band or resonance centred around 250 Hz. This resonance is the most significant acoustic feature in the sound signature of the BMW740 that can be visually identified in the Colour Map. The engine orders in this frequency band would almost certainly interact, generating engine order rumble. A study was therefore initiated to establish if this engine order rumble in the sound signature of the BMW740 was responsible for the high Powerful ratings. The literature review had identified that rumble could affect each of the dimensions of Sound Quality, but there had not been any reported study that had investigated how much rumble would be required to generate a Powerful Sound Quality character without adversely affecting the Refinement related aspects of Sound Quality. Therefore in addition the new study was structured to evaluate the effect of changes to the level of the engine order rumble on the perception of both the Powerful and Refined dimensions of Sound Quality.

Using digital filtering techniques the levels of each of the orders 3E, 3.5E, 4E, 4.5E and 5E were modified. These engine orders were reduced by 3dB, 6dB, 9dB and 12dB, and increased by 3dB and 6dB. A paired comparison jury test was then conducted to subjectively evaluate the effect of these changes on both of the dimensions of Sound Quality. Two questions were posed to the jury subjects. The first asked which of a pair of sounds did they believe to be more Powerful, and the second which of a pair of sounds did they believe to be more Refined. In this way it was possible to establish the effect changes to the level of the engine order rumble on each of the dimensions of Sound Quality. The full matrix of comparisons between the six modified sounds and the original sound was evaluated for each question. The merit scores calculated from the results of each of the two jury studies were combined, and are plotted against each other within a 2-Dimensional Sound Quality Space, illustrated in Figure 18. This is similar to the 2-Dimensional Sound Quality Space or Factor Score Plot established from the Principal Component Analysis of the VAG semantic ratings.

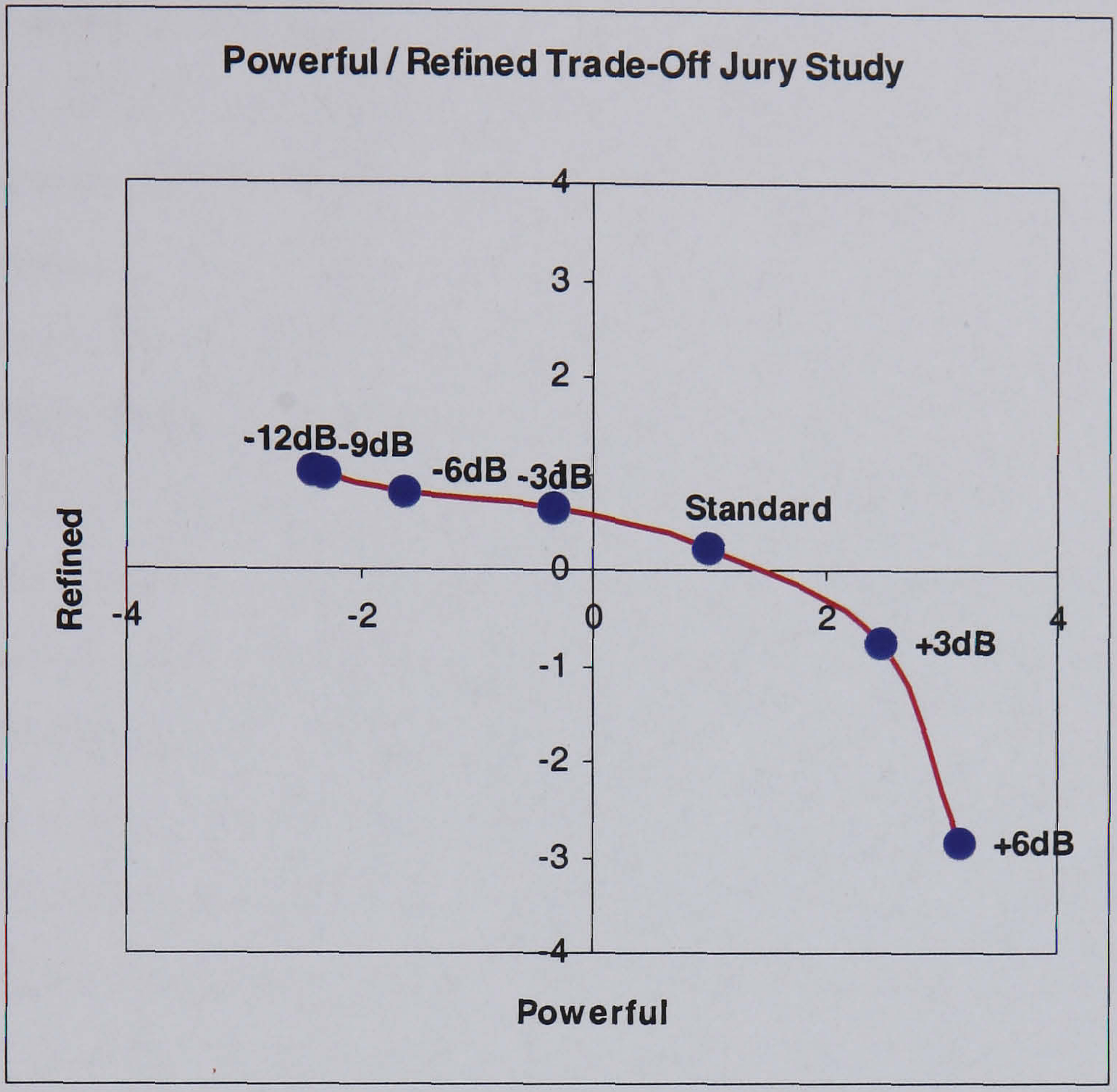


Figure 18: Trade-Off Effect of Engine Order Rumble on Sound Quality Perception

The study has confirmed that it is indeed the presence of the engine order rumble in the sound signature of the BMW740 that is responsible for generating its Powerful sound character. It has also illustrated the trade-off effect between Refinement and Powerfulness for different degrees of engine rumble. This trade-off has demonstrated that engine rumble is required to generate a Powerful subjective impression. Without any rumble the sound is not perceived to be Powerful. This is the transition from the standard position to the –12dB position in Figure 18. However, increasing the degree of engine order rumble degrades the perception of Refinement. If this increase is large then there is a significant degradation in the perception of Refinement. This is the transition from the standard position to the +6dB position. This study has confirmed the findings from the previous literature review that rumble can both degrade the perception of Refinement and enhance the perception of Powerfulness. Through the distribution within the 2-Dimensional Sound Quality Space this study has, for the first time, quantified this trade-off effect.

6.4.3 Effect of High Frequency Engine Harshness on the Refinement Dimension

The engine order rumble illustrated in the colour map of the BMW740 in Figure 17, was the first significant difference between this vehicle and the Jaguar XJ8. The other difference that is clear from these colour maps is the higher levels of high frequency engine harshness in the XJ8, particularly above 1 kHz at high engine speeds. The examination of the Sharpness metric had indicated that the reason why the XJ8 was perceived to have low levels of Refinement was due to higher levels of Sharpness. As Sharpness provides a measure of the high frequency content in a sound, it was concluded that the higher levels of Sharpness in the sound of the XJ8 were due to the increased levels of high frequency engine noise. This has been confirmed through the analysis of the colour maps. The effect of changes to this high frequency engine noise on the perception of Refinement was then examined. Using digital filters the level of the high frequency engine noise on the XJ8 was reduced. A paired comparison jury listening study was then conducted to compare this modified sound with the original XJ8 sound and the sound of all of the other competitor vehicles, asking which sound is more Refined. The calculated merit values from this jury study are illustrated in Figure 19. By reducing the level of the high frequency engine harshness in the XJ8, it was changed from being the least Refined to the most Refined. This study has therefore confirmed that the reason why the XJ8 was perceived to have low levels of Refinement was due to the increased level of Sharpness caused by the high levels of high frequency (1 – 2 kHz) engine harshness at high engine speeds.

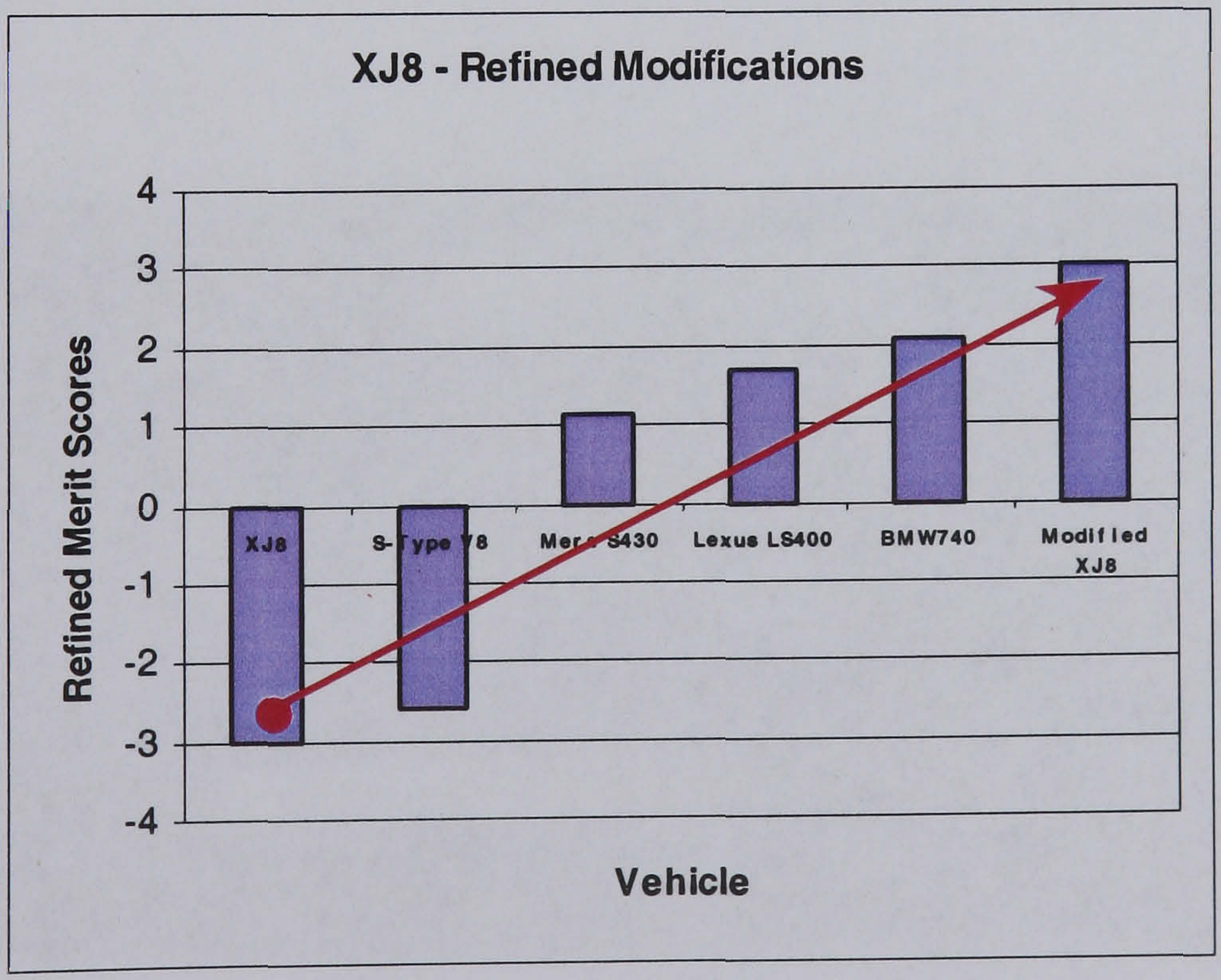


Figure 19: Effect of Reducing the High Frequency Engine Noise in the Jaguar XJ8 on the Perception of Refinement

6.4.4 Summary of Key Acoustic Features

The purpose of the second step in the Sound Quality Engineering Process, *Understanding the Sounds*, was to identify the reasons why the XJ8 was evaluated to be both less Refined and less Powerful than the competition. The examination of the key acoustic features has established that it is the presence of high levels of engine harshness between 1 and 2 kHz at high engine speeds that is the reason why it was perceived to have low levels of Refinement. It was also established that the BMW740 was perceived to be more Powerful due to the presence of low frequency engine order rumble. The XJ8 did not have this same degree of engine order rumble, and consequently it was not perceived to be as Powerful as the BMW740.

Figure 20 summarises the key acoustic features in the sound signature of the XJ8 that were found to be responsible for the low levels of Refinement and the low levels of Powerfulness. The operating condition is a full load acceleration through 1st gear, up-shifting to 2nd gear, accelerating through 2nd gear and up-shifting to 3rd gear. In summary the low levels of Refinement are due to the presence of excessive high frequency harshness at high rpm, and the low levels of Powerfulness are due to the lack of low frequency engine order rumble. These two key acoustic features are indicated in the colour map in Figure 20. The techniques used to identify these acoustic features on the XJ8 have outlined the methodology required to deliver the second element of the Sound Quality Engineering Process, and have addressed the third research objective outlined in Section 4.

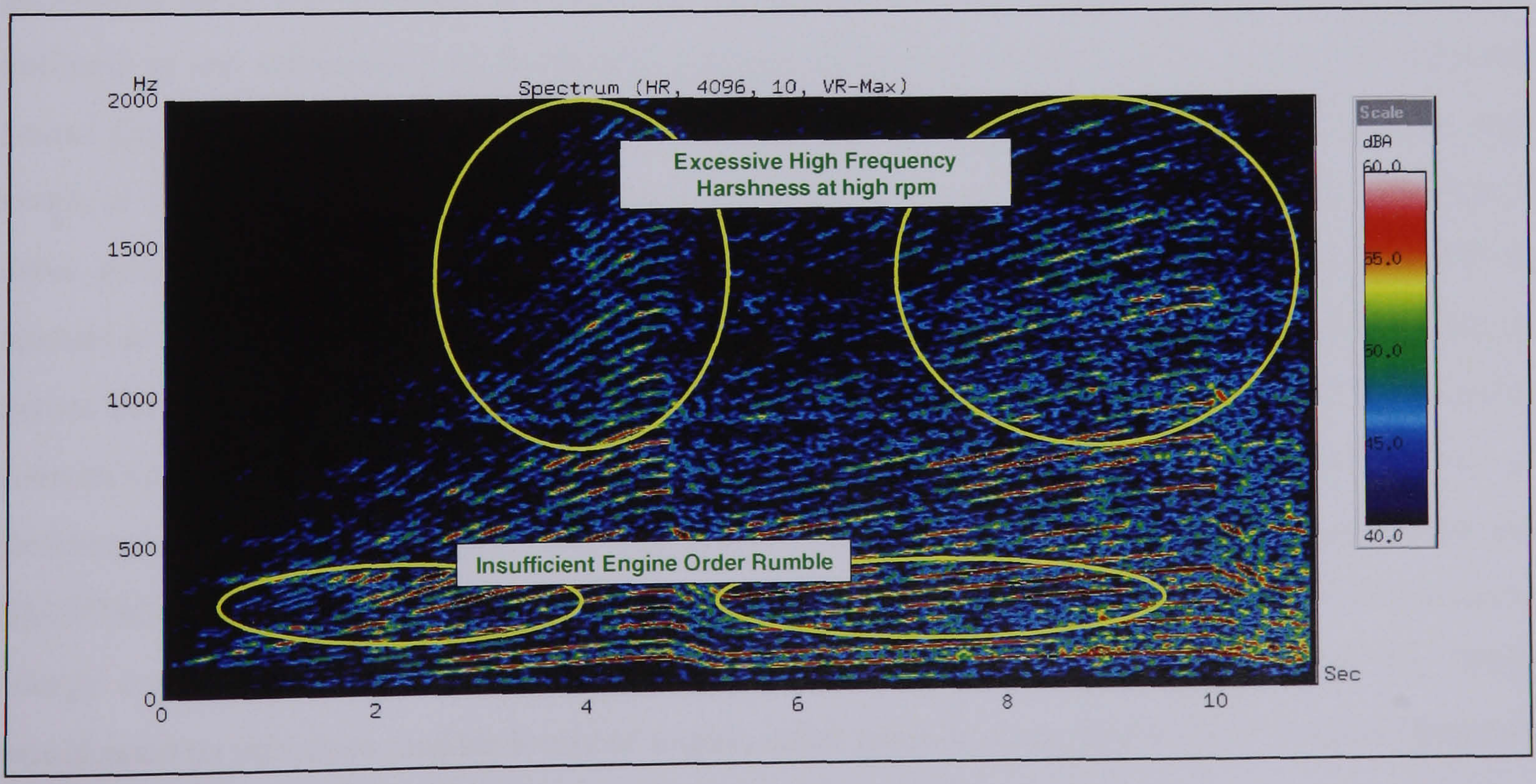


Figure 20: Key Acoustic Features on the Jaguar XJ8

6.5 Understanding the Vehicle & Objective Sound Quality Target Setting

The first two steps of the Sound Quality Engineering Process that have been outlined in the previous sections have focused on quantifying the subjective differences in Sound Quality between the different vehicles, and identifying the key objective acoustic features in the sound signatures that are responsible for generating these subjective differences. However, in order to add engineering value to these findings it is necessary to relate them to the vehicle development process such that they can be used to drive the engineering change needed to modify the nature of the Sound Quality character. The ability to relate changes in the key acoustic features to the design detail and product specification required to deliver the subjective Sound Quality target was the focus of the third step in the concept Sound Quality Engineering Process, *Understanding the Vehicle*.

6.5.1 Identification of the Design Features responsible for the Key Acoustic Features

The first element in this step of the process involved identifying the noise sources and paths that were responsible for generating the key acoustic features identified in the sound signature of the XJ8. Various NVH development technologies such as noise path analysis and sensitivity analysis were applied to identify the noise sources and paths that were responsible for generating these key acoustic features. The detail of this noise source and path identification is outlined in the submission to the EngD portfolio titled *Understanding the Sounds & Objective Sound Quality Target Setting* [26]. To summarise these findings it was established that the high levels of high frequency engine harshness at high rpm on the XJ8 were due to a noisy timing chain drive system, high up-shift engine speeds in the transmission calibration that cause the XJ8 to operate at uncompetitive high and harsh engine speeds, and the lack of sufficient noise attenuation across the bulkhead between the engine bay and the passenger compartment. Each of these noise sources or paths would need to be addressed if the X350 vehicle was to improve upon the levels of Refinement above the existing XJ8. An examination of the noise sources and paths on the BMW740 identified that the source of the low frequency engine order rumble was structure-borne energy transmitted across the gearbox cross-member in the middle of the floorpan. The X350 would need to introduce similar levels of engine order rumble as the BMW740 if it was to improve upon the Powerful sound character of the existing XJ8.

6.5.2 Development of a Sound Quality Target Sound

One of the aims of the Sound Quality Engineering Process was to develop a Sound Quality target sound for a new vehicle programme. However, such a target sound would need to, on the one hand, reflect the subjective Sound Quality requirements, and on the other hand, drive the vehicle development process. There would be little point developing a Sound Quality target sound if it was not known how it could be engineered into the product. Consequently a process was developed to create a Sound Quality target sound that took these two requirements into consideration. The following sections detail the pilot application of this process to develop a Sound Quality target sound for the new X350 vehicle programme.

6.5.2.1 Digital Filter Modifications

The development of a Sound Quality target sound for the new X350 vehicle programme was based upon the application of digital filter modifications to the sound recording of the existing XJ8 vehicle to simulate the effect of changes to the noise sources and paths that were responsible for generating the previously identified key acoustic features. The digital filters were applied to the sound recordings using the MTS Sound Quality software. These simulations were based upon knowledge of the design detail changes required to achieve them. It was established that the high frequency harshness on the XJ8 was due to the timing chain whine, high up-shift calibration speed and inadequate noise attenuation across the bulkhead between the engine bay and the passenger compartment. It was known that a silent timing chain drive system could be engineered into the V8 engine, and consequently the timing chain orders were digitally removed from the sound recording of the XJ8. The effect of reducing the up-shift calibration speed from 6900 rpm to 6400 rpm on the XJ8 was simulated by cutting the time period out of the sound recording of the XJ8 between these two speeds. Finally the effect of fitting a full secondary bulkhead between the engine bay and the passenger compartment was simulated by applying a notch filter to reduce the high frequency engine harshness by a level equivalent to the expected increase in bulkhead attenuation achieved by fitting the secondary bulkhead. To enhance the powerful characteristics, the effect of tuning the structure-borne energy transmitted across the gearbox mount and through the gearbox cross-member, as per the BMW740, was simulated by increasing the level of the engine orders between 3E and 5E, to increase the low frequency engine order rumble. Each of these four simulated modifications that were applied to the sound recording of the existing XJ8 are illustrated in Figure 21, along with the resultant X350 concept Sound Quality target sound.

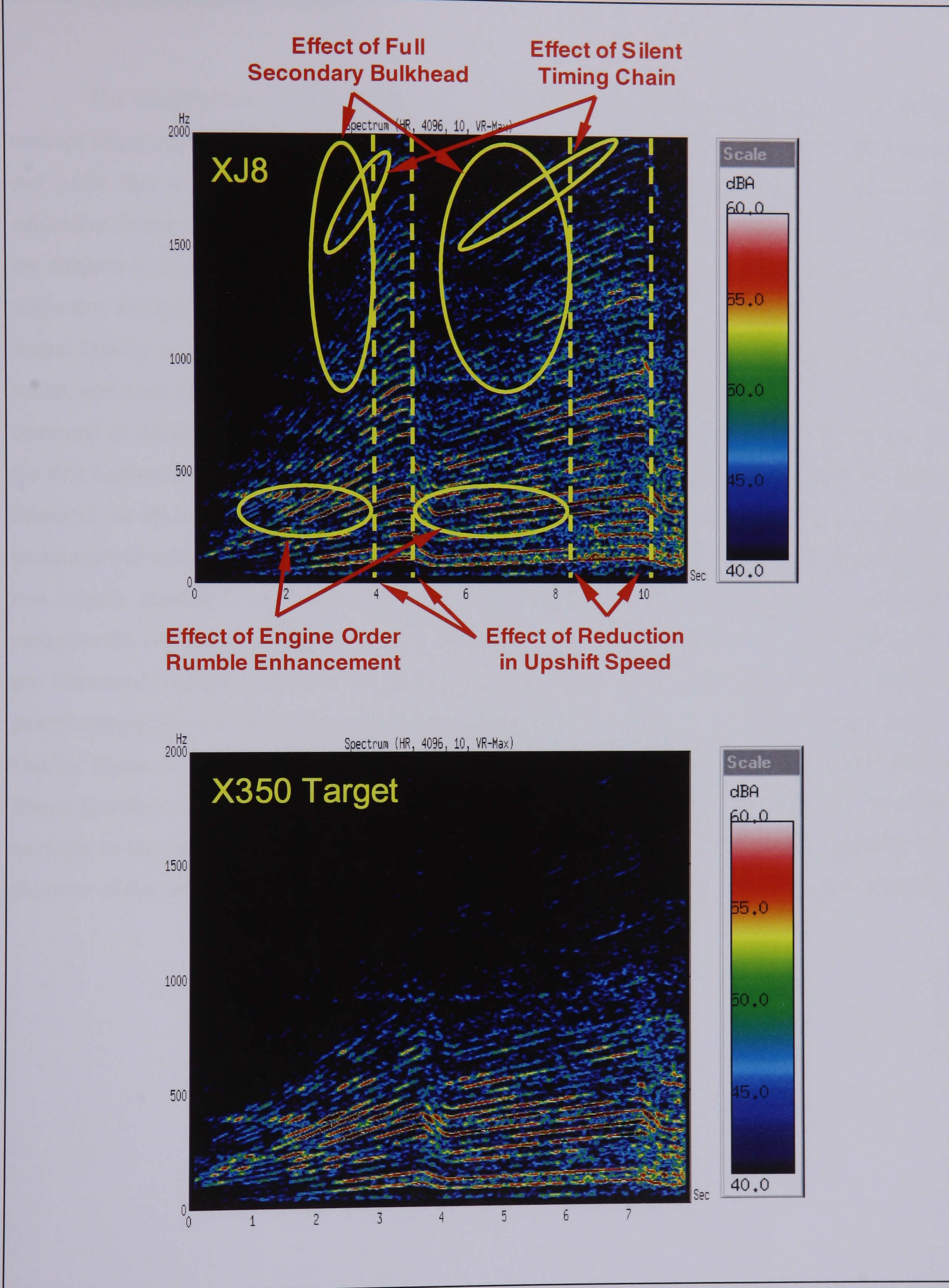


Figure 21: Modifications Applied to the XJ8 & the Resulting X350 Concept Target Sound

6.5.2.2 *Jury Testing Confirmation*

The modifications applied to the sound recording of the XJ8 vehicle to develop the X350 concept target sound were based upon the predicted effects of modifications to the noise sources and paths that were responsible for generating the key acoustic features that determined the subjective Sound Quality character. These modifications would therefore have caused a change in the subjective Sound Quality character of the sound. It was necessary to quantify this level of subjective change. This was achieved through a jury evaluation listening study that compared the Sound Quality characters of the original XJ8 sound recording with the new X350 concept target sound, and each of the other competitor vehicles within the large luxury vehicle sector. The study consisted of three sections, which each used the Paired Comparison jury evaluation technique. In the first section the jury subjects were asked to select which of the two sounds presented was more Powerful. In the second section the jury subjects were asked to select which of the two sounds presented was more Refined. In the third section the jury subjects were asked to select which of the two sounds presented they preferred. Each sound was compared with every other sound to complete the full matrix of paired comparisons. The results of all three sections of this jury study are illustrated in Figure 22. The calculated merit scores for each of the Powerful and Refined paired comparison questions are plotted against each other to represent the 2-Dimensional Sound Quality Space. In this way it was possible to illustrate the change in the underlying nature of the Sound Quality of the X350 concept target sound over the existing XJ8. The results of the third question in the jury study, which asked which sound was most preferred, are represented by the diameter of the red circles for each vehicle, the larger circles representing greater preference levels.

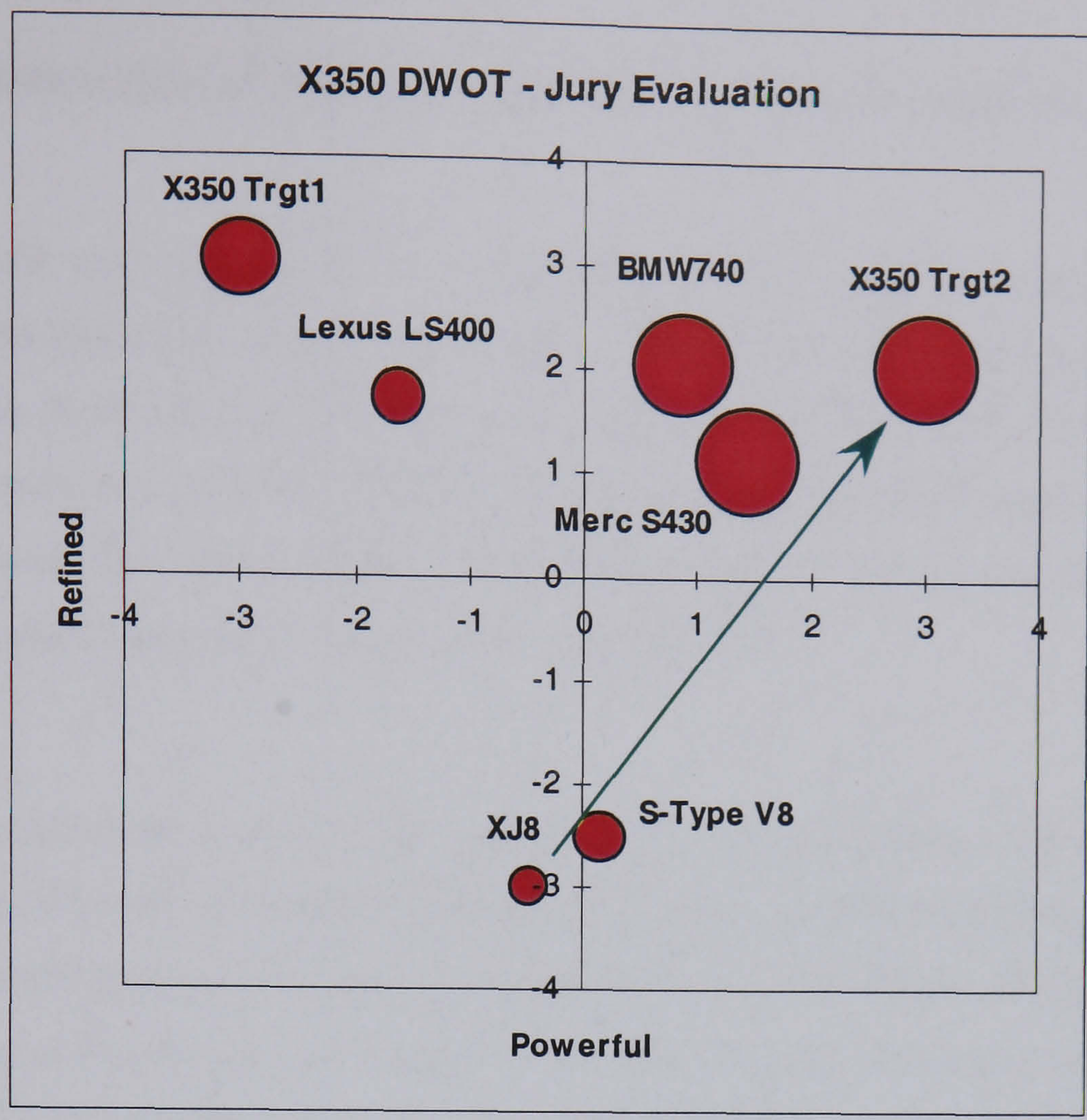


Figure 22: Results of Jury Testing Confirmation

The modifications applied to the sound recording of the XJ8 to develop the X350 concept target sound, indicated as X350 Trgt2, have improved both dimensions of Sound Quality. The Refinement levels have been improved, and the Powerful character has been enhanced. These modifications have changed the XJ8 sound from being the least preferred to a sound that is comparable in preference to the leading competitors. Note that the vehicle sound in Figure 22 that is labelled X350 Trgt1 was an initial X350 concept target sound that was based only on simulated modifications to the high frequency engine harshness of the XJ8. It did not include any enhancements to the level of the low frequency engine order rumble. The location of this concept target sound within the 2-Dimensional Sound Quality Space has indicated that without the enhancement to the level of the low frequency engine order rumble only the Refinement levels have been improved. The Powerful character has not been enhanced.

The pilot application on the X350 vehicle programme has demonstrated that the jury listening study can be used to provide a means of quantifying the nature of the Sound Quality character of a concept target sound, in terms of the underlying dimensions of Sound Quality and in terms of the overall preference for Sound Quality.

6.5.2.3 *Comparison with the Subjective Sound Quality Target and Required Improvements*

One of the requirements of the Sound Quality target sound was that it delivered the previously defined subjective Sound Quality target. This subjective target had been defined as a target area within the 2-Dimensional Sound Quality Space that was derived from the Principal Component Analysis of the VAG semantic differential drive appraisal ratings. It is necessary therefore to compare this 2-Dimensional Sound Quality Space with that derived from the paired comparison jury study. This comparison is illustrated in Figure 23.

It is not possible to use the results of the jury evaluation listening study to confirm that the X350 concept target sound will result in a vehicle that when evaluated would locate exactly within the subjective Sound Quality target area. The comparison between the two 2D Spaces can only be used to confirm that the directional changes to the Sound Quality character of the concept target sound meets the required improvements to each of the dimensions of Sound Quality that have been identified as a result of the subjective target setting process. The evaluation of the simulated modifications through the jury study have demonstrated that both the Refinement levels and the Powerful character have been improved. They have resulted in the same diagonal translation of the XJ8 towards the upper right hand quadrant of the 2-Dimensional Sound Quality space that had been identified to deliver the required improvements to each of the dimensions of Sound Quality. The expectation therefore is that these modifications will work towards the delivery of the subjective Sound Quality target. The initial X350 concept target sound, labelled as X350 Trgt1 in Figure 23, on the other hand did not indicate that this diagonal translation would be achieved and consequently it can be concluded that the modifications to only the sources and paths responsible for the high frequency engine harshness would not deliver the subjective Sound Quality target. Therefore, whilst not being able to confirm that the final X350 concept target sound would locate exactly in the brand target area, the predicted changes to each of the dimensions of Sound Quality can be used to identify what needs to be done to the X350 such that it overcomes the shortfalls of the XJ8. As an engineering tool this is exactly what is required at the target setting and concept stage of the vehicle development programme.

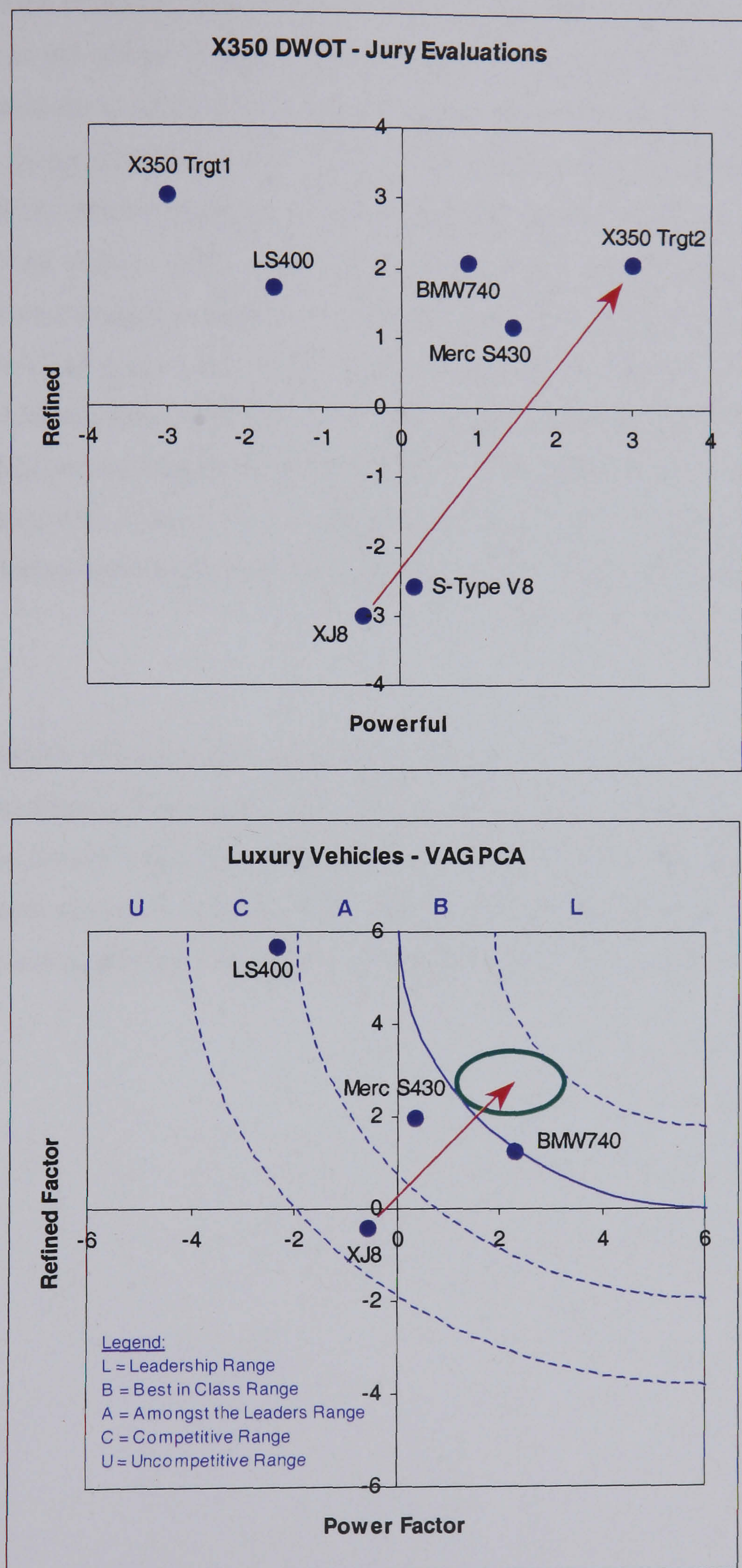


Figure 23: Comparison of Jury Study Results with Subjective Sound Quality Target

The key success of the techniques developed has been the ability to relate the modifications to each of the key acoustic features that are required to change the subjective Sound Quality character to the design changes required to achieve these modifications. It was possible to use the evaluation of the resulting X350 concept target sound to drive the implementation of each of the identified design feature changes. This has provided the strategic direction for the NVH development of X350 vehicle programme by identifying the design fundamentals that are necessary to deliver the Sound Quality target. The delivery of the final Sound Quality performance will ultimately be achieved through the application of traditional NVH development technology, but at the pre-development and target setting stage the key requirement is that the critical design features and architecture fundamentals are built into the programme assumptions. The process applied to develop the X350 target sound has provided the ability to relate the subjective Sound Quality target to the design features and architecture fundamentals that are needed to deliver this target, and has consequently delivered this requirement. This has addressed the fourth research objective outlined in Section 4.

The techniques developed and outlined over the last few sections have linked the first three steps of the Sound Quality Engineering Process, *Understanding the Requirements of the Sounds*, *Understanding the Sounds* and *Understanding the Vehicle*. They have developed the capability of applying a structured approach to Sound Quality Engineering that links the customer requirements through the target setting process to the design detail that is needed to meet these requirements.

6.6 Evaluating the Degree of Achievement

At the time of writing the X350 vehicle programme was going through its final stages of development prior to launch. As part of the vehicle sign-off process the latest X350 NVH development prototype vehicle (ESDV404) was evaluated using the VAG Sound Quality appraisal process. The location of this vehicle within the 2-Dimensional Sound Quality space is illustrated in Figure 24. Although the final X350 vehicle made significant improvements over the existing XJ8 it did not quite meet its Best-in-class target area. It did however move from being merely Competitive to being Amongst the Leaders for Sound Quality. It delivered the required improvements to the Refinement dimension of Sound Quality through the application of the three design features previously outlined in Section 6.5.2. However it was not possible to deliver the level of enhancement to the low frequency engine order rumble that was necessary to deliver all of the required improvement to the Powerful dimension. The submission to the EngD portfolio titled *Sound Quality Engineering Process, Implementation & Measures of Success* [43] outlines in detail the reason for this shortfall.

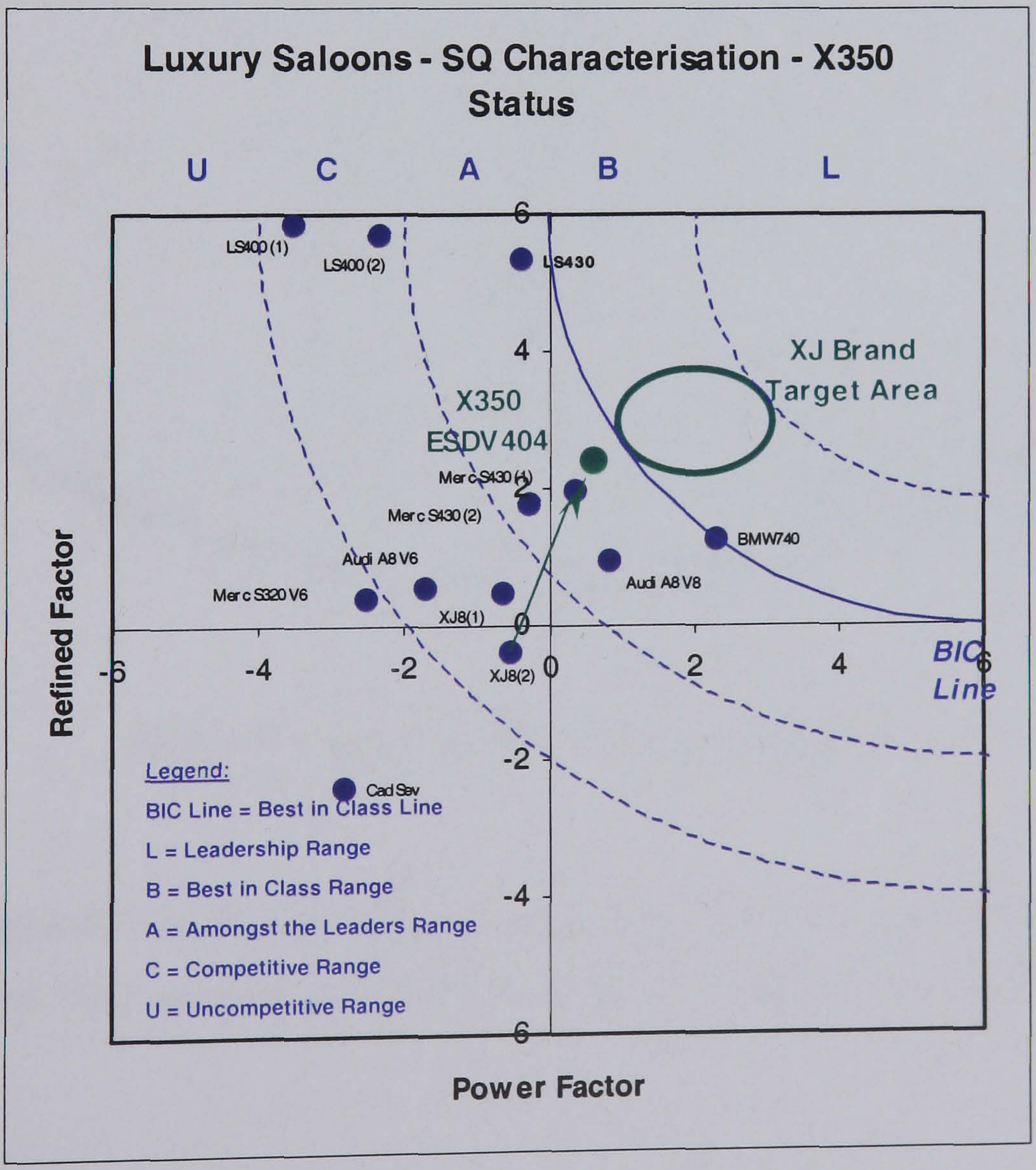


Figure 24: Final Degree of Achievement on the X350 Vehicle Programme

7. Sound Quality Engineering Process

The principal aim of the EngD research was to develop a Sound Quality Engineering Process that can be incorporated within the existing vehicle development process at Jaguar Cars. The final completed version of the Sound Quality Engineering Process that has been implemented at Jaguar is illustrated in Figure 25. It is based upon the findings established from each of the work packages detailed in the previous section. Although it is described as a process it is rather a methodology for delivering Sound Quality applied within the vehicle development process.

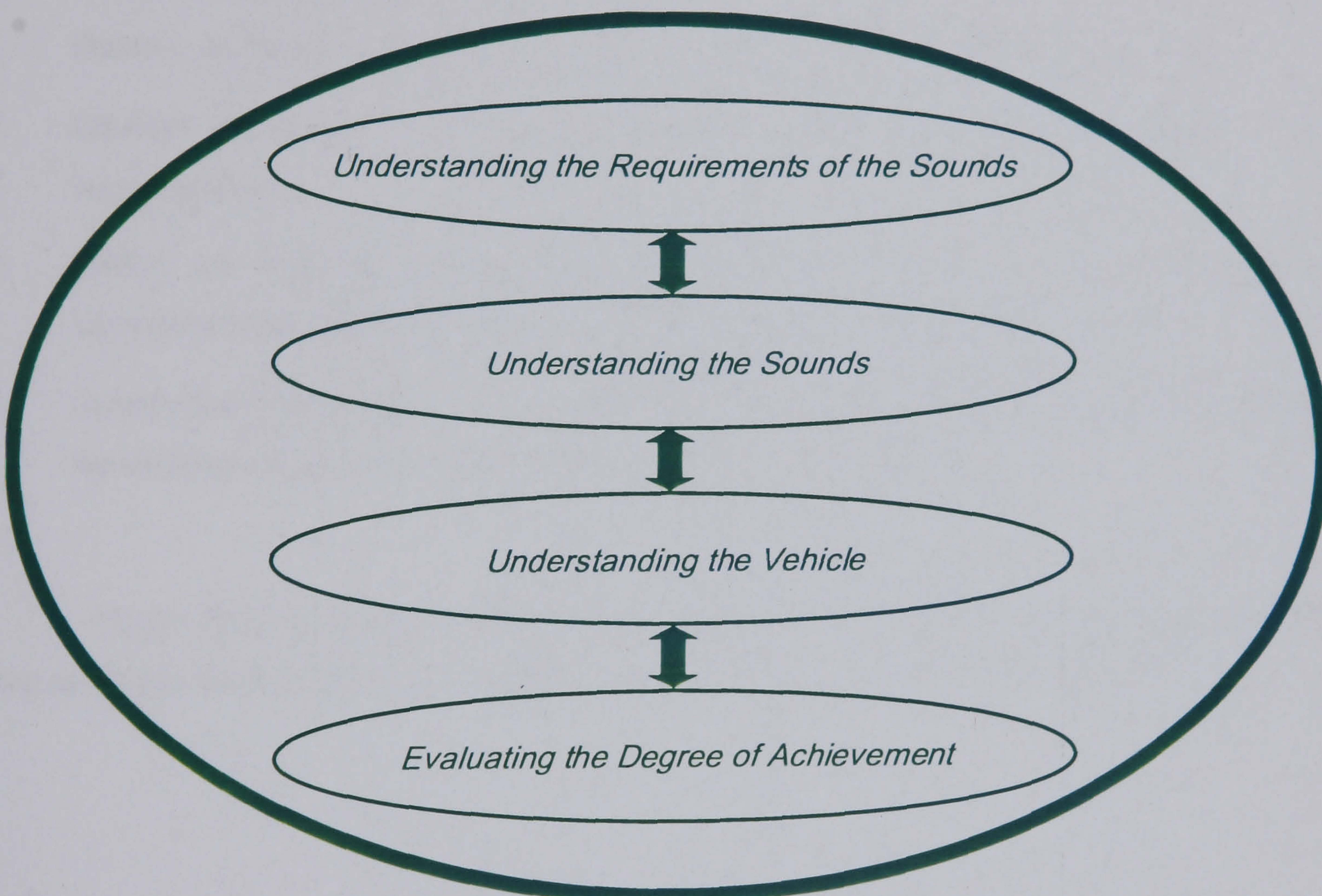


Figure 25: Sound Quality Engineering Process

The completed Sound Quality Engineering process consists of four integrated steps. The process is focused on translating the subjective customer requirements to the vehicle design specification.

The first step in the process is referred to as *Understanding the Requirements of the Sounds*. It involves quantifying the distribution of Sound Quality within a particular vehicle segment and then targeting the subjective Sound Quality to support the vehicle programme's PALS target. There are six specific elements that deliver this step in the process. These are:

1. Subjectively assess the Sound Quality character of a vehicle using the Semantic Differential Evaluation technique within the VAG drive appraisal process.
2. Illustrate the Sound Quality character in the form of the Sound Quality Polar Profile Plot.
3. Combine the results of all the vehicles assessed and use Principal Component Analysis to illustrate its location within the 2-Dimensional Powerful/Refined Sound Quality Space.
4. Establish the vehicle level requirements for the Sound Quality character using the PALS targeting process.
5. Define the Segment Specific Subjective Sound Quality Target Area within the 2-Dimensional Sound Quality Space required to deliver the PALS target.
6. Identify the Improvements to each of the Dimensions of Sound Quality that are required over the existing vehicle to deliver the subjective Sound Quality target.

Figure 26 illustrates each of these six elements implemented on the X350 programme. This step in the process has addressed the first and second research objectives outlined in Section 4.

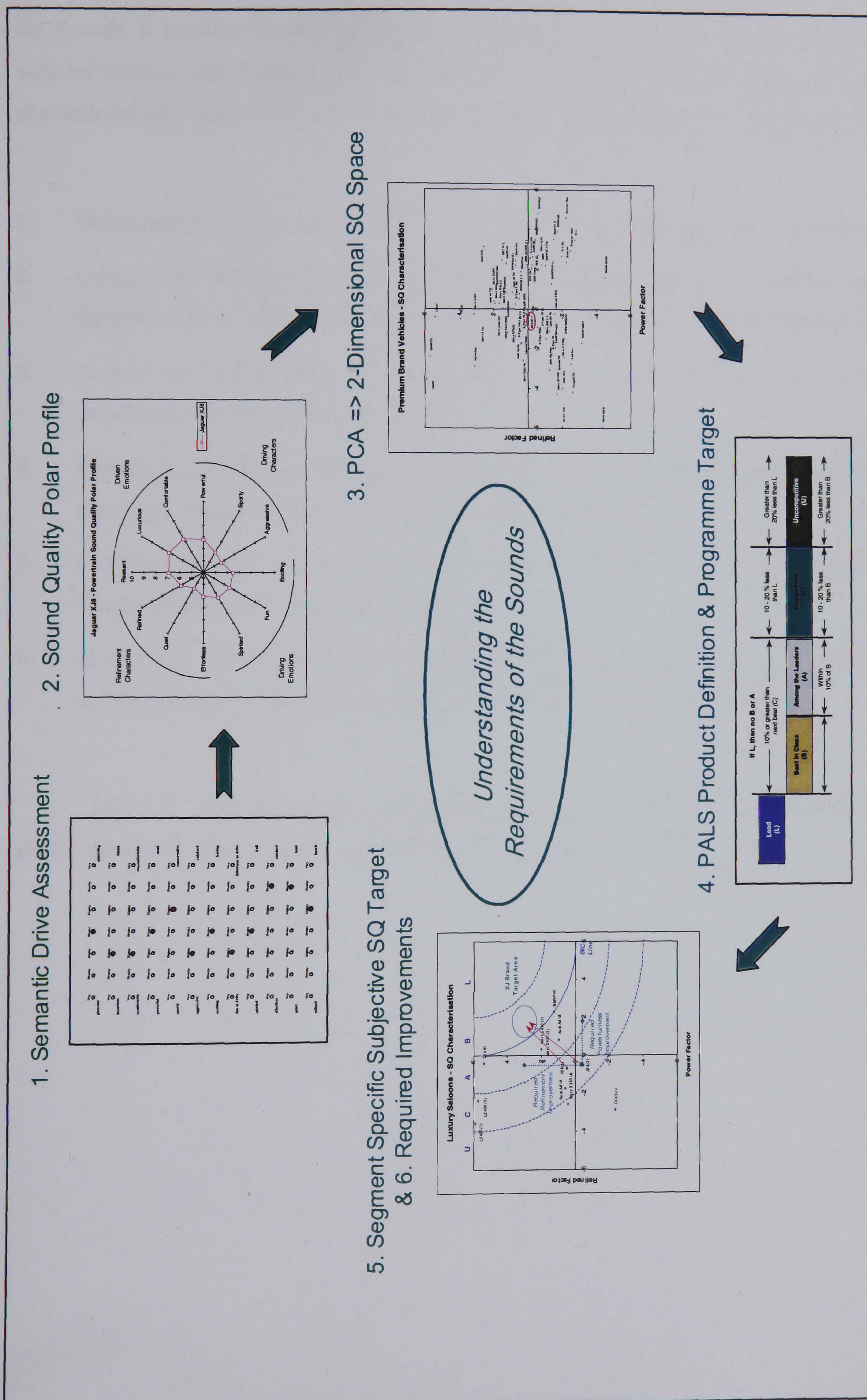


Figure 26: Elements of Step 1 in the Sound Quality Engineering Process

The second step in the Sound Quality Engineering Process is referred to as *Understanding the Sounds*. It involves identifying the key acoustic features within the sound signatures of the vehicles within a vehicle segment that are responsible for determining the differences in subjective character between them. There are six specific elements that deliver this step in the process:

1. Benchmark the interior sound of each of the vehicles in a particular vehicle segment.
2. Compare the overall Loudness and Sharpness levels of the vehicles to identify fundamental differences in the Sound Quality character between the vehicles within the vehicle segment.
3. Analyse the engine order harmonic patterns over the full operating engine speed of the vehicle through the use of colour maps.
4. Use the Sound Quality Analysis system to evaluate the subjective effect of modifications to the engine order patterns and other acoustic features.
5. Confirm the effect of changes in the level of the acoustic features on the subjective Sound Quality perception through jury evaluations.
6. Identify the changes to the key acoustic features required to deliver the improvements to each of the dimensions of Sound Quality identified from Step 1 of the process.

Figure 27 illustrates each of these six elements implemented on the X350 programme. This step in the process has addressed the third research objective outlined in Section 4.

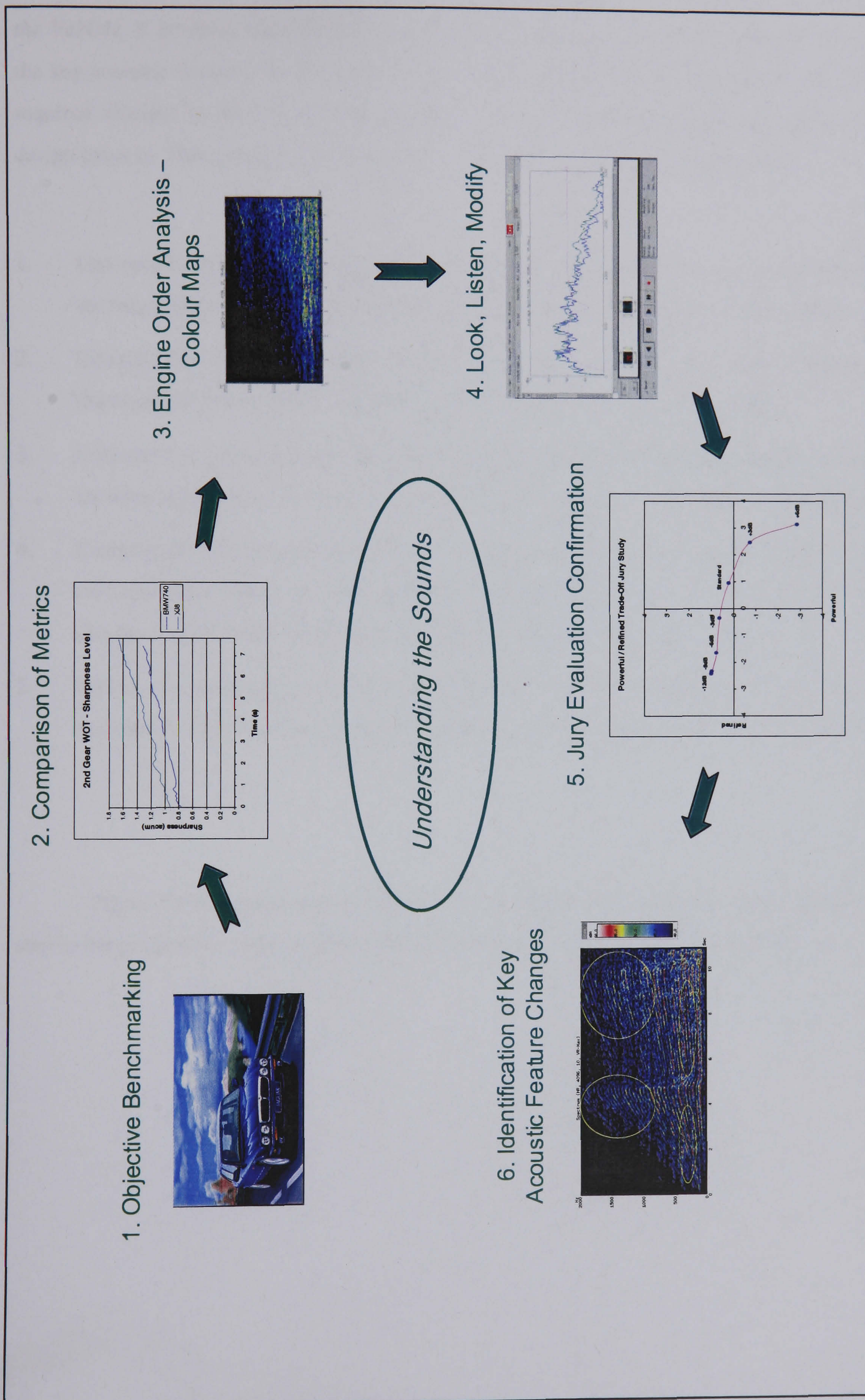


Figure 27: Elements of Step 2 in the Sound Quality Engineering Process

The third step in the Sound Quality Engineering Process is referred to as *Understanding the Vehicle*. It involves identifying the noise sources and paths that are responsible for generating the key acoustic features. It then involves relating changes to these noise sources and paths to the required changes to the key acoustic features to set Sound Quality targets and drive the vehicle design process. There are five specific elements that deliver this step in the process.

1. Use established NVH development techniques to identify the noise sources and paths that are responsible for generating the key acoustic features within the sound signatures.
2. Simulate the effect of changes to these noise sources and paths by applying digital filters to the sound recording of the donor vehicle to develop a concept target sound.
3. Evaluate this concept target sound through jury evaluation listening studies, in terms of its location within the 2D Sound Quality space and its preference relative to its competitors.
4. Compare the directional change in the Sound Quality character from the donor sound to the concept target sound with the required improvement to each of the dimensions of Sound Quality defined when setting the subjective Sound Quality target in Step 1.
5. Identify the architecture fundamentals required to deliver the target and ensure that they are included within the programme assumptions at the concept stage of the vehicle programme.

Figure 28 illustrates each of these six elements implemented on the X350 programme. This step in the process has addressed the fourth research objective outlined in Section 4.

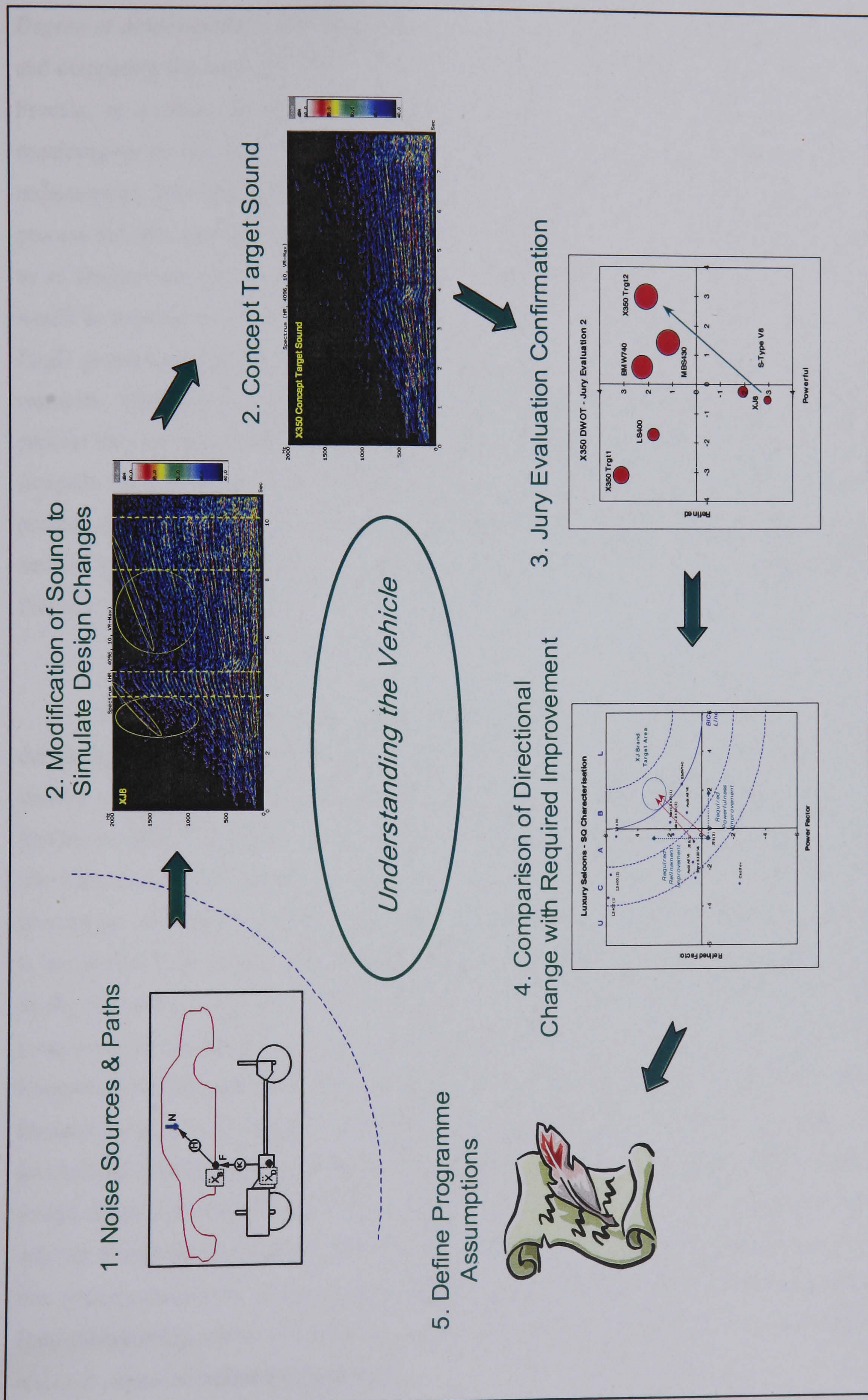


Figure 28: Elements of Step 3 in the Sound Quality Engineering Process

The final step in the Sound Quality Engineering Process is referred to as *Evaluating the Degree of Achievement*. It involves assessing the final degree of achievement of Sound Quality, and comparing this with the initial subjective target. It completes the Sound Quality Engineering Process, as it relates the final degree of achievement expressed in terms of the customer level requirements to the initial subjective Sound Quality target that was defined to deliver these requirements. This step has replaced the fourth step that had been formulated in the initial concept process that was outlined in Section 6.1. In this initial concept process the fourth step was referred to as *Engineering the Vehicle*, and involved identifying the NVH development technology that would be required to deliver the subjective vehicle level Sound Quality target. However, during the EngD programme the identification of this technology was found to lie outside the scope of the research. Although these technologies are an essential part of the overall NVH development process they are not unique to the new Sound Quality Engineering Process. They are necessary to integrate the process within the vehicle development process, but are not actual elements of the process itself. For this reason it was found that the initial fifth research objective outlined in Section 4 was not a necessary element in the development of the Sound Quality Engineering Process.

The Sound Quality Engineering process is essentially based around target setting, driving the design process to deliver the target, and evaluating the degree of achievement. The key to the success of the process is its ability to use the subjective customer level requirements for Sound Quality to drive the vehicle design. This was the specific requirement identified to address the shortfalls in the NVH development process at Jaguar that were outlined in Section 3. The new process has enabled the nature of the Sound Quality of Jaguar's existing vehicles to be quantified. It has provided the means of developing a subjective Sound Quality target that defines the degree of improvement required over an existing vehicle to deliver the requirements for a new vehicle programme. It has developed a structured approach that identifies the key acoustic features that are responsible for the subjective Sound Quality character and the changes required to these acoustic features to deliver the required Sound Quality improvements. The most important step in the process has been its ability to relate the required improvements to the key acoustic features to the design detail and vehicle specification changes necessary to deliver these improvements. In this way the Sound Quality Engineering Process is not simply an isolated target setting process, but one that actually drives the vehicle design. The new Sound Quality Engineering Process has therefore been incorporated within the existing vehicle development process. This was the sixth and final research objective outlined in Section 4.

8. Implementation of the Sound Quality Engineering Process

The Sound Quality Engineering Process that was originally developed on the X350 vehicle programme has since been implemented on all of the other new vehicle programmes at Jaguar Cars. The implementation of the process on each of these vehicle programmes is detailed in the submission to the EngD portfolio titled *Sound Quality Engineering Process, Implementation & Measures of Success* [43].

It has been implemented on the new S-Type R vehicle programme, which was launched in early 2002. In contrast to the X350 vehicle programme it was possible to enhance the level of the engine order rumble on this vehicle to achieve the required improvement to the Powerful dimension of Sound Quality. The design detail that was identified also delivered significant improvements to the high frequency engine harshness. However, the high levels of remaining supercharger whine resulted in the S-Type R failing to deliver the required improvement to the Refinement dimension of Sound Quality. The process was also applied to the target setting process of the new F-Type Roadster programme to develop both a subjective Sound Quality target and a Sound Quality target sound for this new addition to the Jaguar product portfolio. It was possible to use actual Roadster customers to evaluate the Sound Quality character of the concept target sound and to confirm that it delivered their Sound Quality requirements. Unfortunately the new F-Type vehicle programme is currently on hold, and consequently it has not been possible to continue the implementation of the Sound Quality Engineering Process on this vehicle. The process has also been implemented on the new XK8 and XKR vehicles programmes. Again it was possible to use actual Sports Car customers to evaluate the Sound Quality character of the concept target sound. This vehicle programme is currently underway and the elements of the Sound Quality Engineering continue to be implemented. Elements of the process have also been applied to the X-Type vehicle programme. The Sound Quality Engineering Process has been seen as a success at Jaguar and continues to be an integrated part of the vehicle development process.

Finally, as a result of disseminating the work of the EngD research throughout the Ford Motor Company, elements of the Sound Quality Engineering Process have been applied within Land Rover, and within the North American Ford car and truck brands.

9. Discussion

The purpose of the EngD research was to develop a Sound Quality Engineering Process that could be integrated within the vehicle development process at Jaguar Cars. This process has been developed through its pilot application on the X350 vehicle programme and, as outlined in the previous section, has been rolled-out to all of the other new vehicle programmes at Jaguar. Through the initial development and the subsequent implementation of the process a number of key learning points have been established. The following sections outline these key learning points. In addition the principal strengths and weaknesses of the process are outlined and reviewed.

9.1 Key Learning Points

Prior to initiating the EngD programme of research into Sound Quality Engineering, Jaguar did not have any means of incorporating the delivery of the customer requirements for Sound Quality within the vehicle development process. This had resulted in Jaguar's products trailing the competition in the delivery of Sound Quality. The principal reason for this was that Jaguar did not have any understanding of the nature of Sound Quality. As a result it had no means of quantifying and targeting Sound Quality to capture the customer requirements. The first area that needed to be addressed therefore was the development of an understanding of the nature of Sound Quality. Through the research it was established that it is possible to reduce the characterisation of Sound Quality to two underlying dimensions. These two dimensions are a measure of the Refinement levels and a measure of the Powerful sound character. This was the first key learning point established from the research.

The review of the published literature had demonstrated that a number of previous researchers had also attempted to characterise the nature of Sound Quality in terms of the underlying dimensions. However all of this previous work was based upon an analysis of the results of jury listening tests. Their findings consequently did not reflect the underlying nature of Sound Quality as perceived by the customer when actually driving the vehicles. There was also disagreement amongst the previous researchers as to the number and nature of the underlying dimensions. Some had identified two underlying dimensions, whilst others had identified three. There was concern about the analysis conducted by these previous researchers to interpret their results. The evaluation of the Sound Quality through the VAG process, and the subsequent analysis and critical review of the results, has addressed each of these issues and has confirmed that the underlying nature of Sound Quality can be represented by two dimensions, a Refined Factor and a Powerful Factor.

All of the previous findings were based upon sounds from mainstream vehicles fitted with I4 engine configurations. None of the work had focussed on the Sound Quality of premium high performance sports and saloon cars. The EngD research work was purely focused on these premium vehicles, and consequently it was possible to characterise the Sound Quality of all of the vehicles competing in these vehicle sectors. This was achieved by illustrating their locations within the 2-Dimensional Sound Quality Space, the axes of which are defined by the Refined and Powerful dimensions. This has provided Jaguar with the means of quantifying the Sound Quality of all of its own vehicles and all of the vehicles of its competitors. The development of an understanding of the differences in Sound Quality between Jaguar's vehicles and the vehicles of each of its competitors has been the next key learning point established from the research. It has confirmed that Jaguar's existing products are neither as Refined, nor do they have as Powerful a sound character as the competition.

By identifying the areas within the 2-Dimensional Sound Quality Space over which the vehicles from a particular vehicle manufacturer were located, it was possible to identify underlying Sound Quality characteristics for each of the brands competing in the luxury vehicle sectors. The Sound Quality characteristics of the Lexus brand of vehicles was identified to be high levels of Refinement but low levels of Powerful sound character. The Mercedes brand was identified to be less Refined, but with equal levels of Powerful sound character. The BMW brand was identified to be slightly less Refined again, but had the most Powerful sound character for all the saloon vehicle brands. The Jaguar brand was identified to be both less Refined than the Mercedes brand and less Powerful than the BMW brand. The ability to quantify the nature of the Sound Quality of different brands of luxury vehicles within the 2-Dimensional Sound Quality Space has demonstrated that Sound Quality can be used as means of differentiating between different brands of vehicles. This was the next key learning point established from the research.

By examining the distribution in the location of all of the different vehicles within the 2-Dimensional Sound Quality Space it was established that there is a trade-off between the delivery of Power and Refinement. No single vehicle was found to deliver high levels of both Refinement and Power. This implied that the targeting of Sound Quality must involve a balance between the each of the two dimensions. The requirement to set Sound Quality targets that deliver a balance between Power and Refinement that takes this trade-off effect into account was the next key learning point from the research.

The review of the published literature identified six acoustic features that had previously been found to affect the subjective perception of vehicle sounds. When these findings were applied to the sound recordings of the luxury sector vehicles it was established that only a limited number of these features accounted for the differences in the subjective characters. It was established that both the Loudness level and the Sharpness level provide a good measure of the Refinement related aspects of Sound Quality. However, none of the other standard metrics had been found to account for the difference in the Powerful sound character of the vehicles. The review of the published literature had suggested that the roughness generated by engine order rumble could affect the Powerful aspects of Sound Quality. It was also suggested that this rumble could affect the Refinement aspects. However, there had not been any reported study that had investigated the trade-off effect of rumble on both of the dimensions of Sound Quality. The examination of the sound signature of the BMW740 confirmed that it was the presence of engine order rumble that was responsible for the Powerful character of this vehicle. This examination also quantified the trade-off effect of this acoustic feature on both of the dimensions of Sound Quality. It confirmed that engine order rumble is required in order to generate a Powerful character, but as the level of rumble increases the perception of Refinement decreases. If this increase is large then there is a significant degradation in the perception of Refinement. The identification of the trade-off effect of engine order rumble on both dimensions of Sound Quality was the next key learning point established from the research.

The fact that the acoustic features identified from the previous research did not account for all of the differences in Sound Quality between the vehicles was also a significant finding. This highlighted the need not to simply accept the findings established from previous Sound Quality research work when attempting to identify the reasons for the difference in Sound Quality between sets of vehicles. Whilst the findings reported by these previous researchers were correct for the sounds used in their studies, they should not be taken to represent the fundamental or generic factors that account for differences in the perception of Sound Quality for all vehicles. Rather, the research has demonstrated that the best means of identifying the differences amongst a given set of vehicles is through a comparison of their engine order distributions, illustrated in the form of colour maps. The comparison of the changes in the engine orders or harmonic patterns over the operating speed of the engine was the only means that was found that could identify the key acoustic features responsible for the differences in the subjective Sound Quality perception. This was the next key learning point established from the research.

It was established that the reason why the subjective Sound Quality character of Jaguar's existing vehicles were less preferred than the competition was because they were evaluated to be both less Refined and less Powerful than the competition. The examination of the key acoustic features between the vehicles established that for all of Jaguar's existing products the low levels of Refinement were primarily due to excessive levels of high frequency engine harshness at high engine speeds, and that the low levels of Powerfulness were due to the absence of engine order rumble. Both of these key acoustic features would need to be addressed if Jaguar was to improve the Sound Quality of its vehicles. This was the next, and possibly the most significant key finding established from the research. Previously the activities of the NVH department at Jaguar had only been focussed on improving the Refinement levels of its vehicles. The research work demonstrated that if Jaguar were to continue to only focus on the Refinement levels then it would never have delivered vehicles with Sound Quality characters that were preferred by the customers. This key learning point has resulted in a fundamental change in the activities of the NVH department at Jaguar. The focus is no longer on delivering the Refinement levels alone, but is rather on delivering both the Refinement levels and the Powerful character. This has resulted in the initiation of a number of projects that are aiming to establish the design detail required to enhance the Powerful Sound Quality aspects of Jaguar's vehicles. This continuing additional focus on the Powerful dimension of Sound Quality and the means through which it can be delivered is a direct result of developing and implementing the Sound Quality Engineering Process at Jaguar.

9.2 Review of the Strengths and Weaknesses of the Sound Quality Engineering Process

In addition to the key learning points outlined in the previous section the success of the EngD research can be demonstrated through a review of the strengths and weaknesses of the Sound Quality Engineering Process. The submission to the EngD portfolio titled *Sound Quality Engineering Process, Implementation & Measures of Success* [43] provides a detailed review of the strengths and weaknesses of the Sound Quality Engineering Process that have been established as a result of implementing the process on the different vehicle programmes at Jaguar. The following section summarises the principal strengths and weaknesses that have been identified.

9.2.1 *Strengths of the Sound Quality Engineering Process*

The first significant strength of the process is that it has provided the means of translating the Jaguar core-mark value of Refined Power and the individual programme requirements expressed in terms of the PALS targets into vehicle level targets. This has provided the link between the marketing and vehicle programme requirements and the NVH target setting process that had not previously been in place at Jaguar. The next significant strength of the process is the level of subjectivity that it has introduced to the NVH development process. It has provided the means of incorporating the subjective customer requirements within the NVH target setting process and has developed the means of using these subjective requirements to identify and drive the implementation of the design detail that is necessary to deliver these requirements. Prior to implementing the process the NVH activities at Jaguar had not been focussed on delivering these subjective customer requirements.

The most significant strength of the Sound Quality Engineering process has been the link that it has provided between the targets and the design detail required to deliver these targets. The concept target sounds that were developed were based upon the predicted effect of changes to the noise sources and paths that were responsible for generating the key acoustic features. This has provided a significant improvement over the target setting process that had previously been in use within the NVH Department at Jaguar. This previous process was simply based upon benchmarking the competition and setting targets relative to the leading competitors. These nominal targets did not identify the design detail that was required to achieve them. The strength in the new Sound Quality Engineering Process has been its ability to develop targets in conjunction with an understanding of the changes required to the design detail to deliver these targets. This 'design-focussed' target setting process has been directly responsible for driving significant changes to the fundamental programme assumptions at Jaguar, including the reduction of the up-shift speed within the transmission calibration for all of Jaguar's V8 engine derivatives, the incorporation of a full secondary bulkhead on all of Jaguar's new vehicle programmes, and the adoption of the design detail required to enhance the Powerful Sound Quality character.

9.2.2 Weaknesses of the Sound Quality Engineering Process

There are a number of weaknesses associated with the Sound Quality Engineering Process that need to be outlined. These weaknesses have identified a number of areas where further research is recommended. The first of these relates to the additional time and resources required to implement the process. The biggest resource issue is the time-consuming nature of the jury appraisals, and the willingness of the jury subjects to continue to support these appraisals. Although the company has recognised the importance of the process and is prepared to divert resources to support the jury appraisals it has proven necessary to closely control the number and frequency of jury appraisals to ensure that they do not become a disruptive drain on resources. To date, however, this has not been an issue, but it may become one as the process continues to be implemented on all of Jaguar's new vehicle programmes. Alternative means to using multiple jury studies to evaluate the concept target sounds should therefore be investigated. This is the first area recommended for further research.

The second weakness with the process relates to the jury evaluations used to confirm that the concept target sound delivers the subjective customer requirements. Ideally, actual customers should be used for these jury appraisals. This has been possible for each of the F-Type, XK8 and XKR vehicle programmes, but the ability to use customers for the evaluation is the exception rather than the norm. Consequently it is necessary to use internal Jaguar employees for the jury evaluations. This raises the question however, of how close the Jaguar employees' results correlate with the customer results, and whether or not the preferences expressed by the employees match the preferences expressed by the customers. This is the second area recommended for further research.

The third weakness with the process relates to the comparison of the 2-Dimensional Sound Quality Space derived from the jury studies with the 2-Dimensional Sound Quality Space derived from the Principal Component Analysis of the VAG semantic differential ratings. It has been outlined that at best this comparison can only be used to confirm that the directional change in the Sound Quality character of the concept sound over the donor sound on which it was based, delivers the same directional improvements to each dimension of Sound Quality that were identified in order to deliver the subjective target. It was explained that in practice this is all that is required in order to identify the design detail or architecture fundamentals for the vehicle programme. However, there is a remaining concern over the nature of the stimuli used in each of the two 2-Dimensional Spaces. The jury appraisal results were based upon assessments of sound recordings of fixed gear accelerations, whilst the VAG appraisal results were based upon assessments of multiple vehicle operating conditions following actual drive appraisals of the vehicles. Consequently there is a concern that the evaluation of the concept target sound through the use of the jury appraisal process is an unrealistic representation of what the customer will actually experience when driving the vehicle. The most significant differences between the two sets of data is the lack of brand bias, the lack of the biasing effect of other vehicle attributes such as performance feel, and the lack of interactivity with the sound stimuli when running the jury appraisals. These factors may individually or in combination affect the results of the jury appraisals, and consequently it may not be appropriate to compare the two sets of results. This is an area that is discussed in detail within the EngD portfolio submissions, but no work has been conducted to quantify the effect of these differences, nor to develop an improved process for comparing the concept target sound with the subjective target area. The quantification of these effects and the investigation of alternative approaches for conducting this comparison is the third area recommended for further research.

The Sound Quality Engineering Process is very subjective in nature. It was intentionally developed to be subjective in order to capture the subjective customer requirements. However, the lack of objectivity may be a weakness of the process. In particular it would be very useful if an objective means of quantifying the location of the different vehicles within the 2-Dimensional Sound Quality Space could be developed. The development of objective metrics to quantify each of the dimensions of Sound Quality is therefore the fourth and final area recommended for further research.

The final potential area of weakness in the Sound Quality Engineering Process is the key role that the author plays in ensuring that it continues to be implemented across all of Jaguar's new vehicle programmes. Any new process requires a champion to ensure that the process does not lose momentum following its initial implementation. This has proven to be case for the Sound Quality

Engineering Process. The EngD research programme has identified the techniques required to deliver each step in the process, but during its implementation across the new vehicle programmes at Jaguar it has proven necessary for the author to remain involved and provide guidance on the use of each of the techniques. The author therefore needs to continue to champion the process to ensure its continued implementation at Jaguar. Without the author's continued guidance there is a danger that the rigorous application of each step in the new process may not continue. The NVH Department at Jaguar therefore needs to consider how the process could be continued to be implemented on all of Jaguar's new vehicle programmes if the author was not there to champion it.

9.2.3 Recommendations for Further Research

The review of the weaknesses of the Sound Quality Engineering Process has identified a number of areas that are recommended for further research. These areas are:

- Investigate alternative means of conducting multiple and repetitive jury listening studies to evaluate the suitability of concept target sounds.
- Investigate the level of correlation between the preferences for Sound Quality expressed by Jaguar employees and the preferences for Sound Quality expressed by the actual customers of the vehicles.
- Investigate the level of correlation between the evaluation of Sound Quality using jury listening studies and the evaluation of Sound Quality during actual drive appraisals, considering the nature of the stimuli used, the level of interactivity, and the biasing effects of brand image and other vehicle level functional attributes.
- Develop a means of objectively quantifying each of the dimensions of Sound Quality, such that these objective measures can be used to quantify the location of the vehicle within the 2-Dimensional Sound Quality Space. Such objective measures would need to take into account the time-varying nature of transient vehicle accelerations.

10. Route Map Through the EngD Portfolio

In addition to this Executive Summary there are six major submissions that have been made to the EngD Portfolio. The titles of these submissions are:

- *Subjective Sound Quality Target Setting* [4]
- *Sound Quality Brand Engineering* [25]
- *Understanding the Sounds & Objective Sound Quality Target Setting* [26]
- *Sound Quality Engineering Process, Implementation & Measures of Success* [43]
- *Published Papers & Presentations* [44]
- *Personal Profile* [45]

The EngD research work was focussed on developing the techniques required to introduce a Sound Quality Engineering Process to Jaguar Cars. The work packages of the EngD programme were formulated to deliver each element of the Sound Quality Engineering Process. The first three submissions to the EngD portfolio, *Subjective Sound Quality Target Setting* [4], *Sound Quality Brand Engineering* [25], and *Understanding the Sounds & Objective Sound Quality Target Setting* [26] outline the bulk of the research that was conducted. These three submissions outline how each of the steps of the Sound Quality Engineering Process were developed and then implemented and validated on the X350 vehicle programme. The fourth submission, *Sound Quality Engineering Process, Implementation & Measures of Success* [43], outlines the how the results of the EngD research have been implemented within the engineering business. It details the elements that make up each step of the final version of the Sound Quality Engineering Process, and illustrates how the process has been implemented on all of the new vehicle programmes at Jaguar. It then reviews the success of the process following its implementation across all of these new vehicle programmes. The fifth submission, *Published Papers & Presentations* [44], outlines the papers published and the presentations given that have disseminated the findings of the EngD research work, both internal within the Ford Motor Company, and external to the wider engineering community. The final submission, the *Personal Profile* [45], outlines the personal development of the author over the duration of the EngD research programme, detailing the level achievement in each of the ten required competencies and the results of the 16 engineering management short courses undertaken to support this development.

11. Conclusion

This executive summary has reviewed the work conducted during the EngD research programme into Sound Quality Engineering. The purpose of this research programme was to develop the tools and techniques that would enable a Sound Quality Engineering Process to be incorporated within the existing vehicle development process at Jaguar Cars.

The research began with a review of the importance of Sound Quality to the engineering business. It was demonstrated that prior to the research programme Jaguar's products were trailing the competition in terms of Powertrain NVH and Sound Quality. This review identified that it was not low levels of noise isolation that delivered high levels of customer satisfaction, but rather the delivery of a Sound Quality performance tuned to match the character of the vehicle. The reason why Jaguar's products were not delivering high levels of customer satisfaction was because the NVH Department at Jaguar did not have a focus on the Sound Quality requirements and as a result there was no means of using the customer requirements to drive the design process. This identified the need to develop a Sound Quality target setting process that would take the customer requirements for Sound Quality and incorporate them within the vehicle development process such that they could be used to drive the vehicle design specification.

A Sound Quality Engineering Process, consisting of four steps, was developed in order to address this need. The first step in the process, *Understanding the Requirements of the Sounds*, involved developing a system for quantifying the subjective nature of Sound Quality and then using this system to define subjective Sound Quality targets for the Jaguar product range. The second step in the process, *Understanding the Sounds*, involved identifying the key acoustic features within the sound signatures of the vehicles that were responsible for determining the different subjective characters. The third step in the process, *Understanding the Vehicle*, involved developing an understanding of the design detail that is responsible for generating the key acoustic features in Jaguar's vehicles, and then establishing how predicted modifications to this design detail would affect the subjective Sound Quality character. The fourth step in the process, *Evaluating the Degree of Achievement*, involved evaluating the final degree of achievement in Sound Quality, in the same manner as the customer would perceive it.

The Sound Quality Engineering Process was initially developed and implemented on the X350 vehicle programme at Jaguar. It has since been implemented on all of Jaguar's new vehicle programmes. Through the initial development and the subsequent implementation of the process the benefits of the process to the engineering business at Jaguar have been established. The ability to quantify the Sound Quality character of a vehicle within a 2-Dimensional Space defined by a Power Factor and a Refined Factor has been the most significant of these. This has provided the means of establishing Sound Quality targets that deliver the vehicle programme requirements and that support the delivery of the Jaguar core-mark value of Refined Power. It has been used to identify the improvements to each of the dimensions of Sound Quality over an existing vehicle that are required to deliver this target.

The most significant benefit of the process has been the link that it has provided between the targets and the design detail required to deliver these targets. The concept target sounds that were developed were based upon the predicted effect of changes to the noise sources and paths that were responsible for generating the key acoustic features. This has enabled the development of targets in conjunction with an understanding of the changes required to the design detail to deliver these targets. This 'design-focussed' target setting process has been directly responsible for driving significant changes to the fundamental programme assumptions at Jaguar. There are however, a number of weaknesses associated with the new Sound Quality Engineering Process that need to be addressed, and a number of areas have been recommended for further research and development.

The purpose of the EngD research programme was to introduce a Sound Quality Engineering Process to Jaguar Cars. The findings established from this research programme have been used to develop the techniques required to deliver the four steps of the Sound Quality Engineering Process. The process has been incorporated within the existing vehicle development process at Jaguar and has been successfully implemented on each of Jaguar's new vehicle programmes. It has been directly responsible for driving the engineering change that is necessary to deliver increased levels of customer satisfaction. The EngD research programme has therefore made a direct contribution to the engineering business at Jaguar Cars.

12. References

1. *The Oxford English Dictionary*, 2nd Edition, Oxford : Clarendon Press, 1989.
2. Zwicker, E., & Fastl, H., *Psychoacoustics , Facts and Models*, Springer-Verlag, Heidleberg, 1990.
3. Dimancescu, D., & Dwerger, K., *World Class New Product Development*, Amacom, 1996.
4. Dunne, G.T., 'EngD Submission - *Subjective Sound Quality Target Setting*', The University of Warwick, 1999.
5. Hutchnis, S.M., MacDonald, A.M., Quinn, D.C., & Wright, D.B., 'Noise, Vibration and Harshness for the Customer's Point of View', C389/049, FISITA XXIV Congress, London, 1992.
6. Osgood, C.E., Suci, G.J., & Tannenbaum, P.H., *The Measurement of Meaning*, University of Illinois Press, 1957.
7. Kim, J-O., & Mueller, C.W., 'Introduction to Factor Analysis – What it is and how to do it', Sage University Paper on Quantitative Applications in the Social Sciences, 07-013, Sage, 1978.
8. Kazunori, F., Toichiro, N., & Yoshikazu, Y., 'Research on Sound Quality Evaluation Methods of Exhaust Noise', Society of Automotive Engineers of Japan (JSAE), Vol. 9, No. 2, pp 28-33, 1988.
9. Nakamura, M., 'A Method for Evaluating the Interior Sound Quality of Automobiles', Unikeller Conference, Zurich, 1989.
10. Kozawa, Y., Wakita, T., Hoshino, H., Umemura, Y., & Sugimoto, G., 'A Method of Evaluating Exhaust Sound Quality', Society of Automotive Engineers of Japan (JSAE), Vol. v45, No. 12, pp 37-59, 1991.
11. Okamoto, Y., Furugoori, S., Hirahata, N., Abe, T., & Hata, S., 'Evaluation of Vehicle Sounds through Synthesized Sounds that Respond to Driving Operation', Society of Automotive Engineers of Japan (JSAE), Vol.12, No.4, pp 52-57, 1991.
12. Takanami, K., Iwahara, M., Saito, H., & Sakata, M., 'Improving Interior Noise Produced During Acceleration', Society of Automotive Engineers, Paper 911078, 1991.
13. Wakita, T., 'A Method for Evaluating Exhaust Sound Quality – Steady Speed Sound and Sound Varying with Acceleration', Society of Automotive Engineers of Japan (JSAE), Larger Publications: Proceedings 912, Vol.1, Paper 912123, 1991.
14. Otto, N., & Kuang, C., 'Engine Sound Quality Evaluation Using Semantic Differential Method', Proceedings of the Human Factors Society 36th Annual Meeting, pp 1244-1248,

1992.

15. Hashimoto, T., Saito, H., & Hatano, S., 'Sound Quality Evaluation of Interior Noise – Objective Evaluation of Comfortableness and Powerfulness', Society of Automotive Engineers of Japan (JSAE), Larger Publications: Proceedings 921, Vol.1, Paper 921014, 1992.
16. Takao, H., Hashimoto, T., & Hatano, S., 'Quantification of Subjective Unpleasantness Using Roughness Level', Society of Automotive Engineers, Paper 931332, 1993.
17. Murata, H., Tanaka, H., Takada, H., & Ohsasa, Y., 'Sound Quality Evaluation of Passenger Vehicle Interior Noise', Society of Automotive Engineers, Paper 931347, 1993.
18. Bisping, R., 'Emotional Effect of Car Interior Sounds: Pleasantness and Power and Their Relation to Acoustic Key Features', Society of Automotive Engineers, Paper 951284, 1995.
19. Hashimoto, T., 'Improvement of Sound Quality of Vehicle Noise', Society of Automotive Engineers of Japan (JSAE), Vol. 49, No. 6, pp 65-70, Paper 9536458 1995.
20. Kashiwakura, K., Hashimoto, T., & Hatano, S., 'Sound Quality Estimation of Car Interior Engine Noise at Steady Revolution', Society of Automotive Engineers of Japan (JSAE), Larger Publications: Proceedings 956, Vol. 9, Paper 958391, 1995.
21. Terazawa, N., Kozawa, Y., & Tatsuo, S., 'Evaluation Method of Engine Sound Quality for Compact Sedan with 4 Cylinder Engine During Acceleration', Society of Automotive Engineers of Japan (JSAE), Proceedings 966, Vol. 10, Paper 968443, 1996.
22. Bisping, R., Giehl, S., & Vogt, M., 'A Standardized Scale for the Assessment of Car Interior Sound Quality,' Society of Automotive Engineers, Paper 971976, 1997.
23. Buss, S., Schulte-Fortkamp, B., & Muckel, P., 'Combining Methods to Evaluate Sound Quality', Proceedings of InterNoise 2000 Conference, Nice, 2000.
24. Sato, N., & Miura, Y., 'Study on Exterior Idling Sound Quality Evaluation Method for Diesel Engine Trucks', Society of Automotive Engineers, Paper 1999-01-1739, 2000.
25. Dunne, G.T., 'EngD Submission - *Sound Quality Brand Engineering*', The University of Warwick, 2002.
26. Dunne, G.T., 'EngD Submission – *Understanding the Sounds & Objective Sound Quality Target Setting*', The University of Warwick, 2002.
27. Callow, G.D., 'The Subjective Response of Occupants to the Noise Inside Vehicles', MIRA Research Report 1979/1.
28. Tsuge, K., Kanamaru, K., Kido, T., & Masuda, N., 'A Study of Noise in Vehicle Passenger Compartment during Acceleration', Society of Automotive Engineers, Paper 850965, 1985.
29. Townsend, G., 'A New Approach to the Impulsiveness in the Noise of Motor Vehicles', Autotech '85, Paper C399/246, 1985.

30. Aoki, H., Ishihama, M., Kinoshita, A., 'Effects of Power Plant Vibration on Sound Quality in the Passenger Compartment During Acceleration', Society of Automotive Engineers, Paper 870955, 1985.

31. Russel, M.F., 'Towards and Objective Estiamte of the Subjective Reaction to Diesel Noise', Society of Automotive Engineers, Paper 870958, 1987.

32. Hussain, M., Golles, J., Ronacher, A., & Schiffbanker, H., 'Statistical Evaluation of an Annoyance Index for Engine Noise Recordings', Society of Automotive Engineers, Paper 911080, 1991.

33. Schneider, M., Wilhelm, M., & Alt, N., 'Development of Vehicle Sound Quality – Targets and Methods', Society of Automotive Engineers, Paper 95123, 1995.

34. Ohsasa, Y., & Kadomatsu, K., 'Sound Quality Evaluation of Exhaust Note During Acceleration', Society of Automotive Engineers, Paper 951314, 1995.

35. Maunder, R.M., 'Practical Applications of Sound Quality Analysis Techniques', AutoTech 95, Paper L07/C498 –217, 1995.

36. Blommer, M.A., Amman, S.A., & Otto, N.C., 'The Effect of Powertrain Sound on Perceived Vehicle Performance', Society of Automotive Engineers, Paper 971983, 1997.

37. Widman, U., 'Aurally Adequate Evaluation of Sounds', Proceedings of EuroNoise '98 Confernce, Vol.1, pp 29-45, Munich, 1998.

38. Brandl, F.K., Biermayer, W., 'A New Tool for the Onboard Objective Assessment of Vehicle Interior Noise Quality, Society of Automotive Engineers, Paper 1999-01-1695, Traverse City, 1999.

39. Biermayer, W., 'Examples of Successful Sound Designs for Sports Cars and SUV Applications', AVL Sound Engineering Conference, 22-23 July, Graz, 1999.

40. Ronacher, A. W., Hussain, M., Biermayer, W., & Stucklschwaige, W., 'Evaluating Vehicle Interior Noise Quality Under Transient Driving Conditions', Society of Automotive Engineers, Paper 1999-01-1683, Traverse City, 1999.

41. Naylor, S. & Willats, R., 'The Development of a 'Sports' Tailpipe Noise with Predictions of its Effects on Interior Vehicle Sound Quality', Proceedings for EuroNoise 2000 Confernce, Paper C577/002/2000, pp 369-377, Nice, 2000.

42. David, H.A., *The Method of Paired Comparisons*, Oxford Press, New York, 1988.

43. Dunne, G.T., 'EngD Submission – *Sound Quality Engineering Process, Implementation & Measures of Success*', The University of Warwick, 2002.

44. Dunne, G.T., 'EngD Submission – *Published Papers & Presentations*', The University of Warwick, 2002.

45. Dunne, G.T., 'EngD Submission – *Personal Profile*', The University of Warwick, 2002.

13. Appendices

Appendix A

Vehicle Appraisal Group Sound Quality Semantic Differential Assessment Sheet.

	Very	Notably	Slightly	Neither	Slightly	Notably	Very	
pleasant	O	O	O	O	O	O	O	**annoying**
luxurious	O	O	O	O	O	O	O	**bland**
comfortable	O	O	O	O	O	O	O	**uncomfortable**
powerful	O	O	O	O	O	O	O	**weak**
sporty	O	O	O	O	O	O	O	**conservative**
aggressive	O	O	O	O	O	O	O	**subdued**
exciting	O	O	O	O	O	O	O	**boring**
fun to drive	O	O	O	O	O	O	O	**laborious to drive**
spirited	O	O	O	O	O	O	O	**dull**
effortless	O	O	O	O	O	O	O	**strained**
quiet	O	O	O	O	O	O	O	**loud**
refined	O	O	O	O	O	O	O	**harsh**

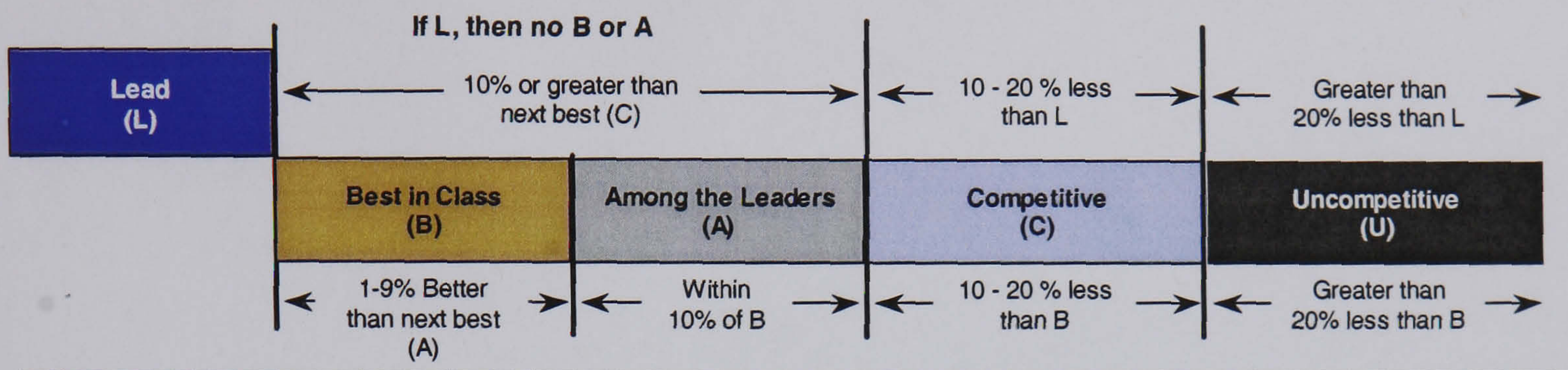
Appendix B

Correlation of initial semantic variables with the derived Principal Components. The critical correlation coefficient at the 99.9% significance level for 72 input vales is 0.3799. The values that exceed this critical value are highlighted in green. The values highlighted in red are those with significant negative correlation, while those that do not illustrate a significant degree of correlation, or alternatively those that illustrate a significant lack of correlation, have been highlighted in blue.

	PC1	PC2
Pleasant	0.61	0.62
Luxurious	0.34	0.82
Comfortable	0.21	0.93
Powerful	0.96	0.06
Sporty	0.93	-0.27
Aggressive	0.84	-0.51
Exciting	0.97	-0.17
Fun	0.98	-0.07
Spirited	0.96	-0.13
Effortless	0.58	0.62
Quiet	-0.28	0.91
Refined	0.03	0.96

Appendix C

PALS categories and classifications.



L (Leadership) is targeted: Brand is at least 10% better than the next best competitor

- Leadership that is memorable, brand defining, clearly discernible to the average consumer.
- If Leadership (L) exists, then there are no Best in Class (B) or Among the Leaders (A) ratings.

B (Best in Class) is targeted: Brand is at least 1%, but not more than 10% better than the next best competitor

- Leadership that is measurable, but not clearly discernible to the average consumer.
- If Best in Class (B) exists, then there is no Leadership (L) rating.

A (Among the Leaders) is targeted: Brand is within 10% of B (Best in Class)

- If Among the Leaders (A) exists, then there is no Leadership (L) rating.
- Attributes that are not brand defining, but are important to the consumer target.

C (Competitive) is targeted: Brand is within 10 to 20% of the best competitor

- Attributes that are not brand defining, and are not as important to the consumer target.
- Attributes where consumers are unable to differentiate performance between the competitive set.