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Vehicle noise primary attribute balance

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Vehicle Noise Primary Attribute Balance

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Abstract

The primary noise attributes in a vehicle are engine, road and wind noise. In terms of human perception, an individual can drive a vehicle over an extended period of time and be left with the feeling that one of these noise attributes dominates. This can be viewed as an imbalance of the noise attributes. Previous investigations in the literature covering primary attribute balance have a bias towards using trained assessors and restricted driving load cases. This paper approaches the optimal balance of noise attributes using customer ratings from an established 'three month in service' industry study. In doing so, this study encompasses a variety of real world driving scenarios and covers a cross-section of the customer demographic base. The aim of the research is to identify the optimal attribute balance from a customer perspective and to link the key factors influencing this perception. In approaching this aim, the underlying acoustic

principles for the interaction of the primary noise attributes are first outlined. The methods used in previously published investigations are summarised and the case for a customer based investigation is made. The scope of existing customer data is reviewed and a methodology to approach the datasets is developed. The interaction of the primary noise attributes is then explored and the Kano quality model is introduced as an aid to explaining the trends seen in the data. In conclusion, the findings of the study are used to suggest a strategy to achieve optimal attribute balance from a customer perspective.

Keywords: Attribute balance; Customer survey; Kano quality model; Sound quality; Vehicle NVH

1. Introduction

A schematic representation of the spectral content of the primary noise attributes in a vehicle is shown in Fig. 1. An example of engine noise compared to the combined engine, road and wind noise is shown in Fig. 2. The data are generated using a Brüel & Kjaer desktop driving simulator [1] which decomposes the measured data into its harmonic and random noise components. The simulator enables the relative contribution of the engine noise to be established from the 'masking' of the, predominantly, road and wind noise contributions. The data shown in Fig. 2 are for a vehicle at a moderate cruising speed of 112 kph. The darker, blue, spectra shows derived engine noise and the lighter, red, spectra shows the combined engine, road and wind noise. It can be seen from Figs. 1 and 2 that each noise attribute contributes over a given frequency range. For engine noise a harmonic signature is present that shapes the lower frequencies in the

overall combined spectra even under the vehicle cruising condition. More detail on the characteristics of vehicle noise is given in references [2-4].

There are three main aspects to consider in achieving attribute balance. First is the overall spectral shape, namely the balance of low and high frequency content which is largely made up of broadband road noise and wind noise, respectively. The second aspect of attribute balance is that of the harmonic content against a broadband spectral background. In practical terms, this relates to how far the engine fundamental frequency and its related harmonics rise above the background of wind and road noise. This may be different depending on whether the vehicle is cruising or is undergoing acceleration. For example, in reference [5] Genell et al investigate this spectral balance in the context of truck cabin noise. Some of the complexity in achieving an optimum balance is reported by Zeitler and Zeller [6] who explore how far the harmonics of the engine sound can rise above the broadband background noise when the vehicle is accelerating whilst still remaining at an appropriate level under cruising conditions. The third aspect of attribute balance involves the directionality of noise sources within a noise attribute. For example, Hoshino and Kato [7] investigate the impact of sound localisation for the wind noise attribute. As a general principle, if a sound can be perceived as emanating from a specific location within the vehicle cabin, for example a door seal, then an imbalance in the sound is likely. Further, it is commonly assumed that if the directionality of the sound is controlled within an individual attribute then the attributes as a whole are more likely to be balanced.

As well as the acoustic characteristics behind attribute balance the driving envelope to which these apply and the role of the person assessing the vehicle noise need to be considered. For example, a customer opinion on attribute balance is typically formed at a variety of speeds, on various road surfaces, under

different environmental conditions and derived over a prolonged period of time. In addition, there is considerable diversity in the demographic of the customer base, with customers having different acoustic tolerances and preferences, two influencing factors being nationality and age. For published investigations in the literature, the assessors are typically professional engineers trained in the specialism of automotive acoustics. The driving envelope used in investigations can be as restricted as a single vehicle speed on a solitary surface [8]. More elaborate investigations use multiple load cases [6] or a more comprehensively constructed drive cycle [9,10]. A simple load case, supported by an objective measurement of the sound gives the opportunity to conduct frequency analysis to compliment the subjective rating obtained. Conversely a comprehensive drive cycle may be far too involved to characterise objectively but will provide a consistent platform for comparing different models and brands of vehicle. The driving simulator used to generate the data shown Fig. 2 offers a relatively new alternative to the methods detailed so far. A simulator model can be built from a minimised set of controlled load cases. The simulator, which interpolates between the conditions, can then be driven in a relatively free condition, or to a specific drive cycle. The use of both a full size and desktop simulator, along with a background on the methodology of the simulators is covered in reference [1].

The subjective opinion of the assessor is captured in a number of ways. At one end of the spectrum, a simple approach can be taken of asking the assessor which attribute is most noticeable, as is done by Hoshino et al [10], for example road noise may stand out over the other attributes. For the J. D. Power and Associates Automotive Performance, Execution and Layout (APEAL) study used in this paper an attribute, such as the sound of the engine, is rated on a scale of 1 to 10. A further extreme is to use a rating scale of semantic pairs, such as that

used by Zeitler and Zeller [6]. This technique uses opposing descriptors such as smooth versus rough or weak versus powerful, with the scores assigned to a relative scale. A detailed subjective description of the tone or nature of the balance of the sound can be achieved using this method. However, care must be taken in choosing the descriptors for the study.

A graphical representation relating the assessor and the driving envelope for publications [5,6 and 8-10] is shown in Fig. 3. Each piece of research is positioned in Fig. 3 according to the driving envelope and the type of assessor used. The x-axis ranges from a real world driving scenario to a specific load case. The y-axis ranges from an untrained customer assessor to an expert professional assessor. As can be seen in Fig. 3 publications [5,6 and 8-10] feature the use of trained assessors and either structured drive cycles or specific load cases. This is typical of the wider published literature on attribute balance. Reference [11] contains an extensive review of the public domain literature on this subject.

This paper documents an investigation which utilises customer input from real world driving scenarios. The aim of the research is to determine an optimal attribute balance from a customer perspective. Thus, understanding customer preferences for attribute balance and identifying the key factors influencing their perceptions are the key objectives for this investigation. A novelty of the work is establishing a link between customer satisfaction scores and customer dissatisfaction problem counts. In Section 2 the methodology of the study is outlined. In Section 3 customer survey results are presented in terms of scatter plots. The attribute roles identified from this analysis are then applied to the Kano quality model [12]. Section 4 summarises the study and offers suggestions in order to achieve an optimal attribute balance.

2. Methodology

In this paper, the data on customer ratings for noise attributes are provided by J. D. Power and Associates, who specialise in consumer research. While using the same sample of customers and the same questionnaire the research is broken into two distinct studies, the Automotive Performance, Execution and Layout (APEAL) Study [13] and the Initial Quality Study (IQS) [14]. The former deals with customer satisfaction and is focused on the fundamental design and performance of the product. A score between 1 and 10 is given for each question. The results are shown as an average score across the sample size which is typically hundreds of responses per vehicle model. The latter study, IQS, focuses on dissatisfaction and essentially asks whether a given fault is present or not. The results are given as a count of problems per hundred vehicles. Both studies cover the first three months of ownership of a vehicle. The studies are produced on an annual basis and cover a wide range of vehicles from compact utility vehicles to large premium sports cars. However, the data used is limited to the American market; with the implication that model specifications and engine choices are biased in this regard along with the demographic profile of customers. The studies cover multiple attributes of a vehicle such as ride and handling. Questions on noise attributes form only part of the study.

The questions relevant to engine, road and wind noise in each study are listed in Table 1. Ideally the questions would ask about the satisfaction with overall attribute balance and then also ask for a rating of each of the primary attributes. It can be seen from Table 1 that neither study asks specifically about attribute balance. The closest question in the APEAL study is that of the

satisfaction with 'overall interior quietness'. The APEAL study does not specifically ask about wind noise or road noise. The closest question related to road noise is the satisfaction with 'quietness over harsh bumps'. The APEAL study covers engine noise by asking after satisfaction with the 'sound of the engine/exhaust during rapid acceleration'. From Table 1 it can be seen that the IQS study covers wind, tyre and 'abnormal engine noises' but it does not have a question asking about the overall quietness or overall attribute balance.

Two analysis scenarios are constructed for the data. The first uses APEAL questions and the second uses a combination of APEAL and IQS questions. The questions are characterised as inputs (x) and outputs (y) of the analysis and are outlined in Fig. 4. Scenario 1 analyses APEAL satisfaction scores where the relationship between the questions of satisfaction with 'quietness over harsh bumps' and 'sound of engine/ exhaust during rapid acceleration' to the question about 'overall interior quietness' can be explored.

Scenario 2 analyses fault counts against overall interior noise satisfaction. While keeping the APEAL 'overall interior quietness' question as the output, a hybrid question scenario is constructed whereby the IQS study questions that represent the primary noise attributes can now be considered as the inputs. Thus, Scenario 2 explores the relationship between the satisfaction data of the APEAL study with the dissatisfaction problem counts of the IQS study. To determine the interaction between the noise attributes scatter plots are generated for each scenario that show graphically the relationship between the inputs and the outputs.

In this paper the analysis uses data relating to premium saloon cars and premium sports cars. The data on premium saloon vehicles is further sub-divided

into large, medium and compact saloon cars. This sub-division allows trends across market segments to be considered. It includes various sizes of saloon car and also allows any difference between a sports car and a premium saloon car to be identified. For any given vehicle segment there is a degree of subjectivity in deciding which specific vehicle models should be included within the segment. Different organisations may have different criteria for defining a vehicle segment. For example, based upon cost or based upon engine size. In this paper the J. D. Power and Associates vehicle segment groupings are used.

Thirty six vehicles from eleven brands feature in the dataset. Positioning of the vehicles in their respective vehicle segments is shown in Table 2. Due to confidentiality constraints the specific vehicle and brand names have not been identified. It can be seen in Table 2 that three, well established, brands have entries in all four vehicle segments. There are five cases where brands have two vehicles in a given segment. Typically, this is the case when the vehicles are mechanically similar but have different body shapes. The Compact Premium segment has the largest variety of brands and vehicles, where as the Large Premium Sporty segment has the least number of vehicles represented. An indication of the sample size for each vehicle is also given in Table 2.

3. Results

3.1 Score distribution

Results for the Scenario 1 analysis are shown graphically as scatter plots in Fig. 5 and Fig. 6. Fig. 5 shows the satisfaction scores for the sub-attribute

'sound of engine/exhaust during rapid acceleration' on the x-axis versus satisfaction with 'overall interior quietness' on the y-axis. Both axes show satisfaction scores over the range of 7 to 10. To aid graphical interpretation a diagonal line is drawn in the lower left corner and the upper right corner. Joining the lines would indicate where satisfaction scores are equal. For example, a score of 7 for 'sound of engine/exhaust during rapid acceleration' equates to a score of 7 for 'overall interior quietness'. Thus, this line represents the case where $y=x$. In Figs. 5 and 6 the satisfaction scores for compact, medium and large premium saloon cars along with large premium sports cars are differentiated by their respective markers. Each data point represents the average satisfaction score across the sample size for each vehicle. A linear line of best fit, based on all the data points, is also shown in Figs. 5 and 6 along with the R^2 value and the equation of the line of best fit. Fig. 6 shows a scatter plot with 'quietness over harsh bumps' as the sub-attribute plotted along the x-axis. Comparing the distribution of results in Fig. 5 and Fig. 6 it can be seen that the scores for 'sound of the engine/exhaust during rapid acceleration' show a wider distribution than the scores for 'quietness over harsh bumps'. This is reflected in the R^2 values where a value of 0.58 is seen for the 'sound of the engine' versus a value of 0.84 for 'quietness over harsh bumps'. This indicates that the 'sound of the engine during acceleration' is less tightly correlated to 'overall interior quietness' than 'quietness over harsh bumps' is with 'overall interior quietness'. The wider distribution is most pronounced in the compact saloon and large sports cars segments. It can be seen in Fig. 6 that for the majority of vehicles the satisfaction score for 'quietness over harsh bumps' is lower than the satisfaction score for 'overall interior quietness'. The main population of scores and the line of best fit in Fig. 6

consequently sit above the diagonal guidelines which show where the scores would be equal.

An inspection of the trends across vehicle segments in Fig. 5 and Fig. 6 shows that the larger premium vehicles tend to have the highest satisfaction scores for 'overall interior quietness', whereas the compact and midsize size vehicles occupy the mid and low score ranges. This suggests some element of absoluteness to the scores, namely a high satisfaction score equates to an objectively quiet vehicle, whichever segment it is in. For the scores to be fully absolute a customer would need a good appreciation of the quietness of vehicles across the segments; this may be the case for a customer who has upgraded through the segments. Customers in the compact segment may not be familiar with how quiet a vehicle in the large premium segment can be and may be more prone to score in a relative way according to what they have experienced in the compact segment. This could account for more of a blurring between the compact and midsize segments. An additional observation from Fig. 5 is that the satisfaction scores for the 'sound of the engine/exhaust during rapid acceleration' have a tighter correlation with 'overall interior quietness' for the midsize and large saloon car segments than for the compact saloon car or premium sports car segments. One explanation for this would be if the midsize and large segment vehicles were engineered to have a refined engine sound rather than an overtly sporty sound.

The Scenario 2 distribution of IQS dissatisfaction fault counts against the APEAL satisfaction scores for 'overall interior quietness' are shown graphically in Fig. 7 to Fig. 10. The 'overall interior quietness' satisfaction scores are shown on the y-axes plotted over the range of values 7 to 10. The IQS fault count scores are shown on the x-axes over the range of values 0 to 10. However, unlike the APEAL

satisfaction scores, the IQS fault count scores may be greater than 10. Fig. 7 to Fig. 9 show a scatter plot for each of the primary attributes. The distribution of the data on the scatter plots takes a different form to that seen for Scenario 1 in Fig. 5 and Fig. 6. This is due to the use of fault counts with the satisfaction scores. It can be seen in Figs. 7-9 that there is generally a broader spread of data points than for Scenario 1 and that this data builds to a frontier, or boundary in the dataset. Frontiers in datasets can be seen where two outcomes are in tension, such as satisfaction with a vehicle's handling ability versus satisfaction with vehicle comfort [15]. In this case the boundary would be termed a 'Pareto frontier' or 'Pareto front'. Characterisation of these frontiers is often achieved through use of complex algorithms where the front represents the optimal trade-off between two or more conflicting outcomes. Reference [16] provides an introduction to the topic of bi-objective and multi-objective optimization. The frontiers presented in the dataset shown in Figs. 7-9 are subtly different and appear when a high fault count for a given attribute impacts on the overall satisfaction. Three outliers from the main wind noise population and boundary are highlighted in Fig. 8. The reason that these values lie beyond the boundary is discussed later in this section.

Application of complex algorithms to characterise the frontiers is outside the scope of this investigation. However, a guideline to the boundary can be achieved by a linear line of best fit through the points at the edge of the frontier. The data points used to calculate the line of best fit are circled in each figure and the equation of the line is also shown. These guidelines enable a simple comparison of the edge of the data populations for each attribute and are overlaid in Fig. 10. The guidelines give an indication of the trend of each attribute but must be viewed as an approximation to the frontier and should be considered with

reference to the distribution of the full population. The development of an algorithm to characterise the frontier coupled with a larger dataset is an opportunity for further research.

The first observation to note from the distribution of results shown in Fig. 7 to Fig. 9 is that the data population is located on the left hand side of the scatter plots. Thus, most vehicles have a low IQS fault count or dissatisfaction score. However, this does not necessarily lead to a high 'overall interior quietness' satisfaction score. This is evident by a large amount of data being in the lower left quadrant of the scatter plots. This data represents vehicles that have low IQS fault count but still have low 'overall interior quietness' satisfaction score. In contrast the data in the upper half of the plots represent vehicles with a high satisfaction score for 'overall interior quietness'. These tend to have a low IQS fault count.

At the edge of the main data population a frontier can be considered for each attribute, illustrated by the guidelines in the figures. At the frontier it is assumed that a point is reached where the IQS fault count has a discernable relationship with the satisfaction score for 'overall interior quietness'. For the wind noise population there are three outliers beyond the frontier. There are vehicles with fault count scores above 7 that at the same time have relatively high 'overall interior quietness' satisfaction scores. For the large sports car segment, convertible models are included in the dataset. Hence, this market segment can be regarded as a special case with potentially noticeable wind noise but with the expectation of this and so still a moderate satisfaction. However, the data points representing vehicles in the compact and the large saloon vehicle segments indicate potential limitations in using a rigidly defined linear frontier for this attribute. For example, it may be the case that a customer would only degrade the 'overall quietness' score by a certain amount, or to a certain threshold, based on

an observation of excessive wind noise. The drive cycle of the customer is relevant in this case and where they may be aware of a wind noise issue, they may not consistently drive at speeds that would provoke the issue. In this case they may be relatively satisfied with the 'overall quietness'.

Comparing the three attributes shown in Fig. 7 to Fig. 9 it can be seen that each of the data populations have different profiles. The wind noise population and its frontier, indicated by the line of best fit at the boundary, shown in Fig. 8, is further to the right than the road noise population and its frontier shown in Fig. 7. This implies that, in general, for a given 'overall interior quietness' satisfaction score a higher fault count for wind noise is recorded than is recorded for road noise. Thus, a customer may recognise wind noise but not degrade the 'overall interior quietness' to the same degree than if they were to recognise road noise. A similar pattern is seen when comparing the wind noise population shown in Fig. 8 to the scores for 'abnormal engine noises' shown in Fig. 9. For ease of visual comparison the guidelines for the three attributes are plotted together in Fig. 10.

With regard to trends across market segments, the count of IQS faults for the larger premium vehicles are generally lower than for the compact vehicles. This follows a similar trend to that seen in the Scenario 1 analysis and indicates a leaning towards absolute performance of the product even though a customer's expectations may be higher for the larger premium vehicle.

3.2 Attribute roles and the Kano quality model

In interpreting the trends seen in the data in Section 3.1 the Kano quality model [12] can be applied in an attempt to understand customer satisfaction. The Kano quality model comes from a product development background and a desire

to understand where effort and resources are best focussed to achieve optimal customer satisfaction. The model was developed by Kano in the 1980's and is now widely used in product development and quality applications. Kano found that there are some basic parts of the product that must be reliable and functional and that failure to achieve this basic quality results in poor customer satisfaction. However, overdevelopment of these parts of the product gives diminishing returns in customer satisfaction. An example of basic quality is the operation of a door handle on a vehicle. At the other end of the scale, some features of the product may not be missed by a customer even though they are not present. However, when executed well these features can give a disproportionately high impact on customer satisfaction. These may also be termed 'surprise and delight' features. For example, a creative approach to interior lighting in a vehicle can achieve 'surprise and delight' for minimal investment. The Kano model consolidates these findings on customer satisfaction and considers three types of quality: basic quality, performance quality and excitement (or surprise and delight) quality and sets a framework for the degree of achievement of an attribute versus the impact on customer satisfaction.

Using the results of Section 3.1 a proposal is shown in Fig. 11 of where the primary noise attributes should be positioned on the Kano quality model and with which types of quality the attributes can be best aligned to. The basic Kano model, with minimal annotation showing the three types of quality, is displayed as an inlay in Fig. 11. The degree of achievement on the x-axis is plotted against 'customer satisfaction' on the y-axis. The three types of quality are represented by three solid, coloured, lines in Fig. 11. A key point is that the relationship between customer satisfaction and the degree to which an attribute is developed or achieved is not always linear. The positioning of the noise attributes is not

absolute but indicative and the noise attributes may also span more than one type of quality, depending upon the load case considered.

The relative location of each noise attribute on Fig. 11 can now be considered, starting with the engine sound. The scatter of results shown in Fig. 5 indicated that customer satisfaction derived from the 'sound of the engine/exhaust during acceleration' was relatively decoupled from 'overall interior quietness'. This probably arises because a customer's impression of the sound of the engine is generally formed when the vehicle is accelerating whereas the noise when cruising may be more influential on the 'overall interior quietness'. Applying this interpretation to the Kano quality model, the sound of the engine accelerating is closer to a surprise and delight feature and, thus, is located closer to the excitement quality line. Note that this is for an acceleration load case. Conversely, 'overall interior quietness' is located closer to the linear performance quality line and is represented by a large ellipse encompassing its sub-attributes. The 'overall interior quietness' is positioned with reference to the cruising load case, where the engine sound would be more subdued. There is, however, a tension between the overall interior quietness when cruising and the sound of the engine under acceleration. This tension is partly due to the engineering limitations of balancing the quietness of the engine when cruising but also producing a pleasing sound when accelerating. This tension is indicated in Fig. 11 by the arrow linking the 'sound of the engine accelerating' with 'overall interior quietness'.

The multiple sub-attributes that contribute to 'overall interior quietness' include road, wind and engine noise in addition to 'quietness over harsh bumps'. These are shown as shaded circles in Fig. 11. Each of the attributes has a bias towards basic quality or performance quality but not one of them could be described as excitement quality. The distribution of customer scores in Fig. 6

indicates a relatively tight relationship between 'quietness over harsh bumps' and 'overall Interior quietness'. However, the scores for 'quietness harsh bumps' are generally lower than for 'overall interior quietness'. This points to 'quietness over harsh bumps' being closer to basic quality rather than performance quality.

In considering where to locate the road and wind noise attributes the frontier results constructed from the Scenario 2 analysis can be considered. A Kano plot illustrates the link between the degree of achievement in an attribute and the degree of customer satisfaction. The relative positions of the frontiers shown in Fig. 10 are analogous to this. A frontier positioned to the right with a high fault count shows that the degree of achievement of the attribute is low, however, this has little impact on the ultimate customer satisfaction. Conversely a frontier positioned to the left indicates a more immediate impact on customer satisfaction if the attribute is not executed well. In this sense road and wind noise can be assigned to different places on the Kano plot shown in Fig. 11, whilst still being closely related to each other. Thus, for equal levels of satisfaction a higher degree of achievement is required for tyre/road noise than for wind noise. From a physical point of view this could be explained by the frequency content of each attribute. Whilst a customer may be able to distinguish between wind and road noise, the lower frequency content of road noise potentially causes more dissatisfaction than the higher frequency content of wind noise [8,9], assuming the directionality and tonal nature of the noise is well controlled in both cases.

'Quietness over harsh bumps' and 'abnormal engine noises' are placed in a similar way in Fig. 11. They feature between performance quality and basic quality and in both cases there is a leaning towards basic quality. As the noise from travelling over a harsh bump is a transient event a poor performance is noticeable when set against a quiet cruising condition. Likewise the tonal nature of engine

noise has the potential to dissatisfy if the sound is prominent against the broadband masking noise.

The non-linear profile of the excitement quality line in the Kano model indicates that there is a limit to the impact on dissatisfaction of not achieving a given attribute. The relative positioning of wind noise in Fig. 11 shows that it is skewed towards excitement quality. This may explain why some of the outliers in the wind noise scatter plots in Fig. 8 do not have more influence on the 'overall Interior quietness'.

An additional example of 'squeaks and rattles' is also shown in Fig. 11 as this demonstrates an extreme of basic quality. There are some noises, such as squeaks and rattles, which serve only to dissatisfy the customer. Such noises should be positioned to the bottom left of the plot.

The Kano model illustrates that customers may have different expectations for different noise attributes and that different attributes can behave in differing impacts on the customer. Fig. 11 summarises the attribute balance required for optimal customer satisfaction. The role of different attributes and different load cases are indicated. For example, Fig. 11 indicates that for a given overall quietness satisfaction, when cruising, a higher level of achievement is required in controlling road noise over wind noise. Since road noise occurs predominantly at lower frequencies this suggests the desired spectra balance or shape to the sound. Engine noise can then be considered, this must be controlled in such a way that lower frequency tonal noise does not impinge upon customer satisfaction. In achieving optimal customer satisfaction, methods to surprise and delight the customer whilst not inhibiting their satisfaction under cruising can be considered. An exhaust system with passive or electronically controlled valves is one way to do this [17]. These systems can limit the exhaust noise when cruising,

thus, contributing to an optimal interior quietness. However, they allow for the exhaust noise to surprise and delight under acceleration.

4. Summary and conclusions

A survey of the extant literature relating to primary noise attribute balance has revealed that previous investigations typically used trained noise assessors and restricted test conditions. This paper has reported on an investigation that uses customer study data. In doing so it encompasses real world driving scenarios and a more complete assessor demographic. The results of two customer studies were used. Each study had a subtly different approach and, therefore, different outputs. One study dealt with customer satisfaction and the other study with perceived faults, or customer dissatisfaction. In a novel approach the satisfaction scores from one study were linked to the dissatisfaction scores from the other. Interpretation of the data was aided by considering frontiers in the data sets.

The results showed different thresholds in the dissatisfaction fault counts for each noise attribute before a relationship with 'overall interior quietness' satisfaction was seen. For example, the relative position of the frontiers for road noise and wind noise indicates that a fault count for road noise more readily impacts on the overall interior noise satisfaction than does a similar fault count for wind noise. A comparison of satisfaction scores showed that the satisfaction with 'overall interior quietness' was more closely correlated with 'quietness over harsh bumps' than with 'sound of the engine/exhaust during rapid acceleration'. The satisfaction with the sound of the engine during acceleration was seen to be relatively independent of overall interior noise for sports car segment. The Kano

quality model was applied to illustrate the non-linear influences of the different attributes on customer satisfaction. The model also showed the potential of noise attributes to surprise and delight the customer.

In conclusion, the findings of this study can now be applied to achieve optimal attribute balance in a vehicle from a customer perspective. Consider first achieving overall interior quietness under cruising conditions. This can be accomplished by bringing the weakest attribute to a level comparable with the other main attributes. The challenge is to characterise how the attributes sit relative to each other and the level of imbalance between them. The scatter plots and Kano model explanations have shown that the absolute value of customer scores for different attributes cannot simply be compared to each other. However, the frontier analysis provides a way to see how each attribute behaves relative to each other. By addressing the weakest attribute and then the next weakest attribute the in turn, the level of imbalance can be reduced. Finally the customer can be surprised and delighted by engineering a suitable sound under acceleration that has minimal compromise with the overall interior quietness when cruising.

In taking the topic further, an attempt could be made to more fully define the frontiers considered in Scenario 2 by the use of a more detailed data set and multi-objective optimization algorithms. The Kano model has highlighted non-linear customer satisfaction trends and an algorithm approach has the potential to characterise these non-linear aspects of the frontiers.

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Fig. 1. Spectral content of the primary noise attributes: schematic representation of engine noise, road noise and wind noise.

Fig. 2. Spectral content of the primary noise attributes: example of the engine noise contribution compared to the combined engine, road and wind noise contributions.

Fig. 3. Graphical representation of the relationship between the assessor and the driving envelope for a number of published investigations into attribute balance.

Fig. 4. Analysis scenarios; with J.D. Power input and output questions

Fig. 5. Scenario 1 J.D. Power APEAL satisfaction scores: scatter plot of 'overall interior quietness' versus 'sound of the engine/exhaust during rapid acceleration'.

Fig. 6. Scenario 1 J.D. Power APEAL satisfaction scores: scatter plot of 'overall interior quietness' versus 'quietness over harsh bumps'.

Fig. 11. Application of the Kano quality model to NVH primary attribute balance.

Table 1

J. D. Power and Associates customer satisfaction study questions relating to the primary noise attributes.

Study title	J.D. Power APEAL (Automotive Performance, Execution and Layout)	J.D. Power IQS (Initial Quality Study)
Scoring method	Satisfaction score (1-10)	Problems per hundred vehicles
Noise questions	<ul style="list-style-type: none"> • 'Overall interior quietness' • 'Quietness over harsh bumps' 	<ul style="list-style-type: none"> • 'Excessive tyre road noise' • 'Excessive wind noise'

-
• ‘Sound of engine/exhaust during rapid acceleration’	• ‘Abnormal engine noises’
-

Table 2

Vehicle brand and J. D. Power segment allocations with vehicle sample sizes.

Brand	Compact Premium Conventional	Midsize Premium Conventional	Large Premium Conventional	Large Premium Sporty
A	Veh. 1 [c]	Veh. 15 [c]	Veh. 26 [b]	Veh. 33 [b]
B	Veh. 2 [c]	Veh. 16 [a]		
C	Veh. 3 [b] & 4 [c]	Veh. 17 [b]	Veh. 27 [a]	
D	Veh. 5 [c]	Veh. 18 [c]	Veh. 30 [c]	Veh. 34 [a] & 35 [b]
E	Veh. 6 [c]	Veh. 23 [c]	Veh. 28 [c]	
F	Veh. 7 [c]	Veh. 21 [d]		
G	Veh. 8 [d]	Veh. 19 [d] & 20 [d]	Veh. 29 [d]	
H	Veh. 9 [d]		Veh. 31 [c]	
I	Veh. 10 [c] & 11 [c]	Veh. 25 [a]		
J	Veh. 12 [c] & 13 [c]	Veh. 22 [b]		
K	Veh. 14 [a]	Veh. 24 [a]	Veh. 32 [a]	Veh. 36 [b]

Sample sizes: [a] <100, [b] 101-300, [c] 301-500, [d] 501+

Fig. 7. Scenario 2 APEAL satisfaction scores and IQS fault counts: scatter plot of 'overall interior quietness' versus 'excessive tyre road noise'.

Fig. 8. Scenario 2 APEAL satisfaction scores and IQS fault counts: scatter plot of 'overall interior quietness' versus 'excessive wind noise problem'.

Fig. 9. Scenario 2 APEAL satisfaction scores and IQS fault counts: scatter plot of 'overall interior quietness' versus 'abnormal engine noises'.

Fig. 10. Scenario 2 APEAL satisfaction scores and IQS fault counts: comparison of the frontiers constructed for wind noise, road noise and abnormal engine noise.