Automotive Aeroacoustic Sound Quality

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Abstract

Aeroacoustic noise sources are becoming increasingly important in the vehicle environment. Research has suggested that for electric vehicles, the predominant focus in development effort shifts from powertrain noise, to masking noises such as road and aeroacoustic. Despite this, the consumer perception of automotive aeroacoustic sound quality is a remarkably under researched field; few examples of literature have previously investigated this area, with fewer still employing qualitative techniques.

This publication summarises a two phase research project. Initially, focus groups were conducted, to gather information on the ways in which a variety of consumer demographics perceive aeroacoustic sound quality. Rigorous grounded theory analysis of the discussions identified six core categories: the perceived acoustic character of the sound, the conditions and environment, the balance of the aeroacoustic sound (spatially, spectrally and relative to other sounds), its noticeability, the expectation of the consumer, and finally their emotional response.

In the second phase, quantitative semantic differential listening studies were carried out using a vehicle simulator. Four principal components were found to explain 85% of the total variance of nine semantic scales: how intrusive the subjects believed the sound to be, how aggressive the aeroacoustic noises were, whether the sounds met the subjects' expectation, and finally whether the sounds were perceived as spatially balanced by the participant.

This study confirms that traditional aeroacoustic performance quantification methods employed by automotive manufacturers, may not be suitable for evaluating a number of the key factors of aeroacoustic sound quality perception. The study also demonstrates the use of a vehicle simulator to assess individual acoustic sources in the presence of other sounds.

1. Introduction

With the increasing popularity of electric vehicles [1], combustion noises traditionally associated with automotive sound quality will be present for a decreasing number of consumers. This shift to electric powertrains changes the interior acoustic environment of a vehicle, potentially increasing the noticeability of 'masking' noises, such as those generated by the road/tyre interaction and aeroacoustic sources.

With this significant change, automotive acoustic engineers should have a clear understanding of the characteristics of these sounds that are perceived as positive or negative. At the time of writing, only a small amount of research had previously been documented in the field of automotive aeroacoustic sound quality [2-5], with even fewer examples utilising qualitative methodologies [6]. Furthermore, no literature was found to have conducted listening studies that varied aeroacoustic signals in isolation, whilst maintaining all other vehicle noises.

Consequently, the objectives of this research project were to:

1. Identify factors that consumers associate with aeroacoustic sound quality;
2. Confirm whether aeroacoustic noises are a positive or negative factor in the vehicle environment;
3. Identify any particular acoustic characteristics of automotive aeroacoustic noise, that lead to a positive or negative perception of sound quality;
4. Conclude whether traditional objective quantification methods for aeroacoustic performance, such as aeroacoustic wind tunnels [7, 8] and computational fluid dynamics [9, 10], correlate with consumer perception.

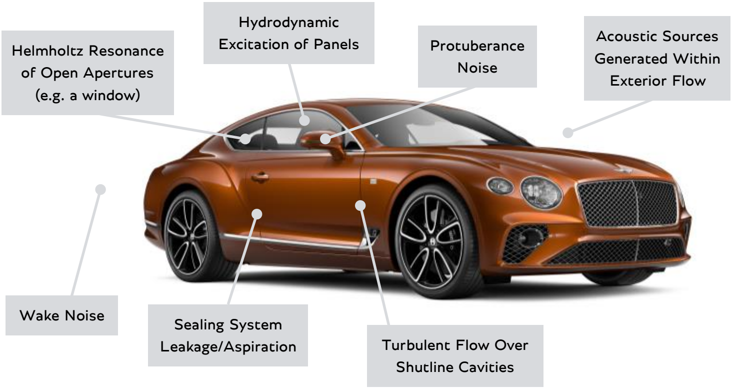
Two main research activities were undertaken to achieve these objectives: a qualitative study (focus groups), and quantitative investigation (a listening study). The results and conclusions of this project can be used to better understand the consumer perception of automotive aeroacoustics, yielding a model of the subjective impression of automotive aeroacoustic noise. Ultimately, providing the ability to make key design decisions to improve perceived aeroacoustic performance in automotive vehicles.

1.1 Automotive Aeroacoustic Noise Sources

Automotive aeroacoustics is not a new topic. A New Scientist article from 1964 discussed how the fast speeds of 'modern' vehicles increased the importance of wind noise [11]. Aeroacoustic noise sources can contribute to the vehicle interior sound via the following mechanisms (shown schematically in Figure 1):

- Stresses in the vehicle exterior flow can generate acoustic sources that travel via the excitation of vehicle panels to an interior receiver [12]. Such phenomena generate a variety of noises, including tones, broadband 'roar' and low frequency wake noises, and can often be characterised by Lighthill's (1952) quadrupole analogy [13];
- As shown by Curle (1955), the interaction of turbulence with a solid body can generate sound propagation as dipole sources, and in the case of external features such as the door mirror, is often referred to as protuberance noise [14];
- Turbulent flow over cavities such as those found between body closing panels (doors, spoilers etc.), can potentially establish a Helmholtz resonance or generate tonal noises via a vortex feedback system [15];
- Gap conditions present in the vehicle glazing/door seals, can allow high velocity air to be drawn into the vehicle cabin, creating monopole, dipole and quadrupole sources [15];
- Fluctuations of the vehicle sealing system due to hydrodynamic pressure can generate a dipole source [15];
- Excitation of the whole vehicle cabin, again via a Helmholtz resonator system due to large open apertures such as a sunroof or door window, can generate high amplitude, low frequency noises; sometimes referred to as 'buffeting' [15];
- Turbulent flow around the vehicle can create hydrodynamic pressure fluctuations on the surface of vehicle panels. However, such excitation has been shown to be weakly correlated with interior noise levels when compared with acoustic excitation [12];
- Aeroacoustic noises can also be generated by any vehicle ancillary components creating fluid flow (air conditioning, engine cooling fans etc.); these will not be discussed in this research.

Figure 1



Schematic of the potential sources of aeroacoustic sounds in a vehicle environment

2. Methodology

2.1 Qualitative Research – Focus Groups

Qualitative interviews in the form of 'focus groups' have been embraced by the market research sector since the 1950s, and were thought to have first been conducted by social scientists during the Second World War [16]. In more recent years, the design and planning of focus groups has been well documented by Richard Krueger; currently a Professor Emeritus at the University of Minnesota [16].

Focus groups promote discussion between individuals, which may lead to a more plentiful disclosure of information when compared with a more intimidating 'one to one' interview [16]. In the wider fields of acoustics, explorative researches into soundscapes such as those conducted by Davies et al (2013), enjoyed success using the focus group methodology [17].

The first question to answer when designing focus groups is: who should be invited to participate? It was concluded that participants with a basic knowledge of aeroacoustic noise should be selected. This ensured that no explanation of what aeroacoustic noises are was required; removing the need for detailed explanations at the beginning.

The first group comprised experts who work directly in the field of automotive aeroacoustics. In order to ascertain whether the opinions of those directly employed in aeroacoustics agreed with the wider population, a second group was convened with experts in other fields of automotive acoustics, sound quality and aerodynamics. Each group involved four or five participants; not including the moderator and assistant.

During the groups, eight questions were asked of the participants to guide the discussion around the research topic: automotive aeroacoustic sound quality [18]. Audio of the sessions was recorded, enabling manual transcription of the comments made by all participants throughout. These comments provided data entries to be analysed as discussed in the following section.

2.1.1 Data Analysis – A Grounded Theory Approach

'Grounded Theory' is a methodology developed by Glaser and Strauss in the 1960s as a tool to develop a theory from collected data [19]. To determine a grounded theory, research begins with no hypothesis or speculated theory, only a research question [20]. Any theories developed are based entirely on data; hence the description grounded.

In order to arrive at a grounded theory for a particular research topic, the researcher analyses the data entries to discover the specific 'concepts' discussed and the broader 'categories' into which the concepts are grouped. It is then possible to determine the 'dimensions' over which these categories vary, for example, concepts within a category labelled 'Perceived Acoustic Characteristic' could vary with the dimension 'Narrowband – Broadband'. The connections between these categories are determined and finally a core category is selected; the central phenomenon around which all other categories are assimilated [21].

In this research, the grounded theory methodology was used as a guide for analysing qualitative data in a methodical and structured manner.

2.2 Quantitative Research – Listening Studies

2.2.1 Noise Vibration & Harshness Vehicle Simulators

Assessment of vehicle sounds during standard operating conditions is challenging. The time taken to modify parts on a vehicle or to move between test vehicles can make subjective assessment difficult, relying heavily on memory. Additional variability can be caused by inconsistent environmental conditions. Completing these assessments in controlled environments such as in a wind tunnel or on a dynamometer is also not without issue; the masking from other vehicle noises is no longer present, rendering perception unrealistic [22].

One potential solution to the issues described above is to utilise a virtual Noise Vibration and Harshness (NVH) vehicle simulator. The Full Vehicle Simulator (FVS) approach described by Kennings et al (2013), provides both sound and vibration inputs to a participant situated in a vehicle environment [23]. Visuals of a moving road are projected on to a screen in front of the vehicle to provide a visual perception of speed. Vibration inputs are applied via the tactile points of the floor pan, seat cushion, seat back and steering column [23]. Audio is provided via electrostatic headphones, and participants use a touch screen in the instrument panel of the vehicle to assess and move between stimuli [23]. To maximise the ecological validity, a full vehicle simulator (Figure 2) was used for the subjective listening studies.

Figure 2

Images of the Full Vehicle Simulator at Bentley Motors Limited

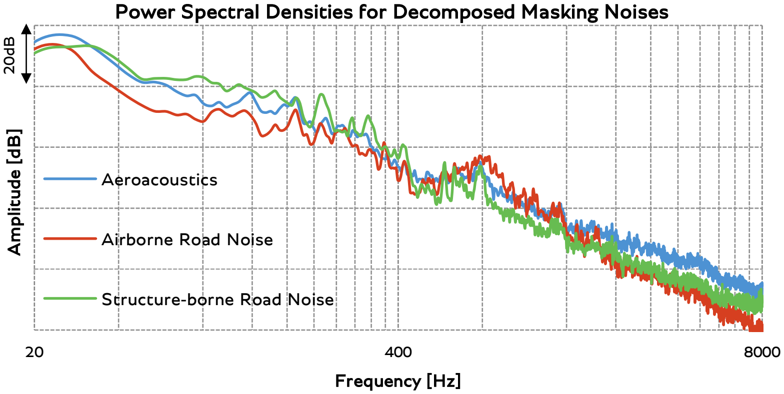
2.2.2 Masking Noise Decomposition

As previously discussed, any assessment of individual acoustic attributes should be conducted in the presence of the other vehicle noises that mask, and as such alter the perception of the attribute in question. In order to manipulate only the aeroacoustic noises in a vehicle interior noise signal, a method for the decomposition of the power-train, structure-borne and airborne road noises was employed.

Operational Transfer Path Analysis (OTPA) has been discussed at length in recent years; with its increase in popularity owing to the vast reduction in time required to complete measurements, when compared with classical transfer path analysis [24]. This method was utilised to provide the ‘Masking Noise Decomposition’ shown in Figure 3, for a luxury saloon vehicle travelling at 140km/h on a smooth road surface. The power spectral densities (PSDs) presented in Figure 3, show the resulting aeroacoustic, airborne and structure-borne road noise sound objects; the stimuli used for the listening study. All harmonic sounds coherent to the revolutions of the engine, at intervals of ½ engine orders for the first fifty orders, were removed using harmonic filtering [25].

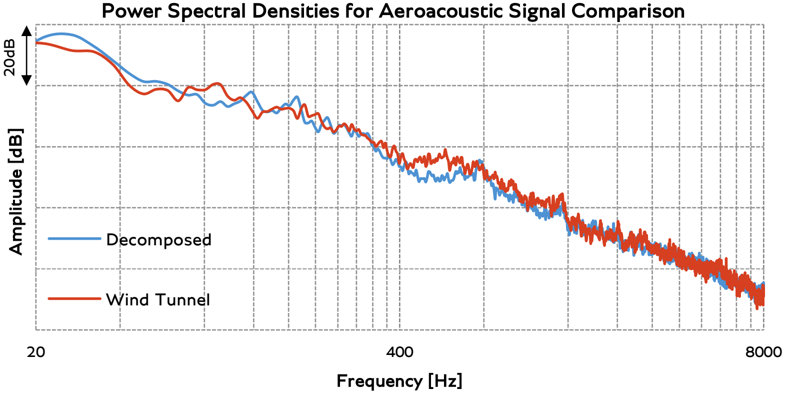
The road-based decomposed aeroacoustic signal from the luxury saloon vehicle, was compared to a wind tunnel measurement for the same type of vehicle; the results can be seen in Figure 4. The PSD of the decomposed signal was generally within 6 dB of the wind tunnel measurement, indicating that this was an adequate approximation.

Figure 3



Power spectral densities for the decomposed masking noises, of a luxury saloon travelling at 140km/h on a smooth road

Figure 4



Power spectral densities for the decomposed and wind tunnel aeroacoustic signal of a luxury saloon at 140km/h road/wind speed

2.2.3 Aeroacoustic Stimuli Generation

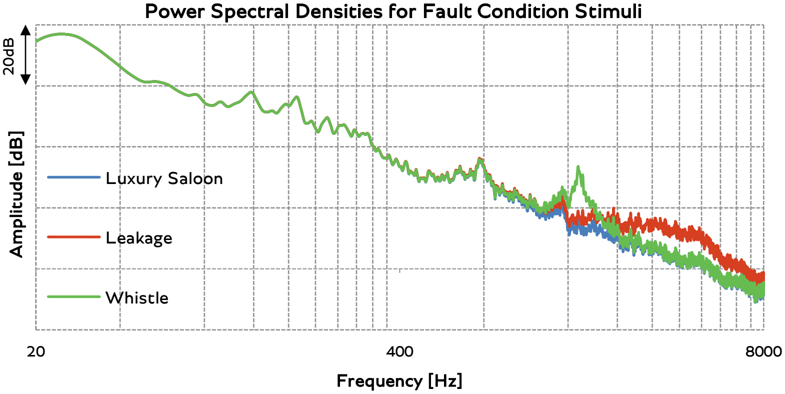
Twelve stimuli were prepared by applying a filter to the aeroacoustic signal derived from the decomposition. Filters were defined to simulate three aspects observed during vehicle development to influence aeroacoustic noise: fault conditions, vehicle type and spectral shape. For some of the stimuli, it was possible to achieve the desired spectral shape by applying a standard Infinite Impulse Response (IIR) filter provided in the NVH simulator software [25]. For others, such as those where the signal was manipulated to approximate the aeroacoustic content of another vehicle type, the PSD of the measured saloon was subtracted from the PSD of the desired vehicle; creating a ‘change’ filter. The change filter was then applied to the original saloon signal as a Finite Impulse Response (FIR) filter. Both approaches gave the advantage of modifying the spectral shape of the signal, whilst maintaining the temporal characteristics found in a road-based recording.

Table 1 provides a short description of each stimulus and the method used for its generation. Two of the stimuli generated to simulate fault conditions can be seen for a single ear position in Figure 5.

Table 1

	Aeroacoustic Stimuli	**Aeroacoustic Stimuli Generation Method**
A	Luxury Saloon	No filter required; standard vehicle
B	Luxury SUV	Saloon aeroacoustics filtered to Sports Utility Vehicle (SUV) using FIR filter
C	Luxury Cabriolet	Saloon aeroacoustics filtered to Cabriolet using FIR filter
D	No Aeroacoustics	Aeroacoustic signal removed; road noise only
E	Whistle (Left Ear)	18dB gain IIR at 1750Hz, width of 100Hz
F	Leakage (Left Ear)	9dB gain IIR at 4000Hz, width of 3000Hz
G	Whistle (Both Ears)	18dB gain IIR at 1750Hz, width of 100Hz
H	Leakage (Both Ears)	9dB gain IIR at 4000Hz, width of 3000Hz
I	Low Frequencies Increased	Saloon filtered to line of best fit with power decrease using FIR filter
J	High Frequencies Increased	Saloon filtered to line of best fit with power increase using FIR filter
K	All Frequencies Increased	Combination of maxima from low and high frequency curves, filtered using FIR filter
L	Luxury Saloon Smoothed	Saloon filtered to line of best fit using FIR filter

Figure 5



Power spectral densities for the original luxury saloon aeroacoustic signal and stimuli with a leakage and whistle added via filtering

2.2.4 Listening Study Design

Using the qualitative conclusions made following the focus group analysis, a listening study was designed to determine the significant factors that influence consumers' impression of aeroacoustic performance. Subjects were presented with recordings, and then asked to rate their emotional response to each stimuli against semantic scales; a common approach in soundscape research [26, 27].

Semantic scales were defined from the 'dimensions' of the categories identified during the focus group analysis, the result of which are presented in section 3.1. Ten semantic word-pairs were selected to capture the key categories also identified in section 3.1:

- Noticeable – Unnoticeable;
- Annoying – Agreeable;
- Unacceptable – Acceptable;
- Cheap – Luxurious;
- Loud – Quiet;
- Uncomfortable – Comfortable;
- Rough – Smooth;
- Unexpected – Expected;
- Unbalanced – Balanced;
- Tiring – Stimulating.

Following an initial training/familiarisation activity, the test participants were asked to rate each aeroacoustic stimuli against each word pair using a 7-point Likert scale; shown in Table 2.

Table 2

Word A						**Word B**
1	**2**	**3**	**4**	**5**	**6**	**7**
Strongly agree with A	Mostly agree with A	Mildly agree with A	Agree with neither	Mildly agree with B	Mostly agree with B	Strongly agree with B

Stimuli presentation order was randomised for each participant. Playback level was calibrated using an artificial binaural head to ensure the signal reproduced in the simulator was of a level equivalent to that observed by an on road occupant. To ensure only aeroacoustic contributions were assessed, the structure-borne road noise, airborne road noise and vibration inputs remained constant for all stimuli, while only the aeroacoustic signal changed. No powertrain sounds were included as it was felt that the omission of exhaust and engine contributions best approximated an electric vehicle; rendering the results and conclusions potentially ‘powertrain neutral’.

24 participants comprising 12 from each gender were invited to participate in the study, ensuring conformity with the ITU-T ‘Recommendation P.800’ for an absolute category rating assessment of audio signals [28].

2.2.5 Data Analysis – Principal Component Analysis

Principal component analysis (PCA) is a variable reduction technique, used to understand whether the variance in large data sets involving numerous variables, can be described by a smaller set of artificial variables; known as the ‘principal components’ [29]. The results of this analysis can be useful if there is a belief that some of the variables included are measuring the same phenomena. A principal component analysis of the results of the listening study was conducted using R (Version 3.5.1), a statistical computing and graphics environment [30], with the aim of identifying the key factors of automotive aeroacoustic perception [29].

To ensure that it was both appropriate and useful to complete a PCA, the data obtained during the listening study was tested using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett’s test of sphericity [29]. To enable direct interpretation of the results, the data was rotated using a Varimax orthogonal rotation [31].

Unless restricted, PCA will calculate the same number of components as input variables. A common method to determine the number of components to extract is to consult the scree plot and retain all components to the left of the inflection point [29]. Four components were extracted, each accounting for ≥15% of the total variance; explaining a cumulative 85% of the original variance.

3. Results and Discussion

3.1 Focus Group Analysis

Following the grounded theory analysis of the focus group recordings, six key categories were identified: Perceived Acoustic Character, Conditions & Environment, Consumer Expectation, Noticeability, Balance and Emotional Response. The ways in which these categories are connected was also determined, demonstrating that all categories linked directly with Consumer Expectation. It was therefore concluded that the expectation of a consumer, prior to exposure to any automotive aeroacoustic sounds, is central to the subsequent perception of quality.

The vehicle environment may influence expectations: “Premium cars over cheaper vehicles; the expectation is that there are no fault conditions (Participant 1D)”. The conditions may also lead to the generation of a particular sound or acoustic character, but if this sound is expected, even if it has high amplitude and dominance, it may indeed be accepted: “You expect it, it’s got an easy solution, and therefore you live with [open aperture buffeting] (Participant 1B)”. If the aeroacoustic sounds are not well balanced: spatially, spectrally or to the other noises in the vehicle (which may vary based on market sector/class), they may be easily noticed: “It is how it is balanced with other [sounds] as well (Participant 1C)”. If these noticeable sounds cannot be controlled by the consumer, the vehicle occupant may become annoyed: “Just an annoyance, constant annoyance, an annoying sound (Participant 2D)”.

Fundamentally, any deviation from what the consumer expects of the aeroacoustics of the vehicle could be described as poor aeroacoustic sound quality, and can thus lead to a negative emotional response. Perhaps suggesting that good quality aeroacoustic sounds are only those that can be described as not noticeable: “good aeroacoustics would be unintrusive, so if you just don’t notice it, it blends in, everything is balanced (Participant 1C)”.

Interestingly there can also be scenarios where aeroacoustic noises may add to an experience, and perhaps lead to a positive emotional response. The increased noticeability of aeroacoustic sounds when driving a convertible with the roof down is both expected and potentially desired: “In a performance car, with the top down, with all that noise, actually, that is what we wanted, we wanted that buffeting noise for the excitement (Participant 2A)”. It is worth noting that these instances were seldom identified by participants in the study, suggesting that aeroacoustic sounds are predominantly a negative contributor to the vehicle environment.

3.2 Listening Study Results

3.2.1 Principal Component Analysis

It was observed during the initial PCA that one of the rotated components was loaded extremely strongly and almost exclusively by the semantic word pair ‘Tiring – Stimulating’. Analysis of the variable correlation matrix indicated that this variable had only ‘low’ correlation with all other variables [32], and as such, could be identified as an independent factor of aeroacoustic perception without inclusion in the PCA. This variable was removed and the principal components recalculated.

The rotated component matrix shows how strongly the variance of each variable is explained by the extracted components; this correlation is referred to as a ‘loading’ [33]. The rotated component matrix for the listening test conducted can be seen in Table 3.

Table 3

	Principal Component (Rotated)			
	1	**2**	**3**	**4**
Proportion of Variance	**0.31**	**0.19**	**0.15**	**0.19**
Noticeable – Unnoticeable	0.80	0.26	0.19	0.27
Annoying – Agreeable	0.67	0.29	0.33	0.42
Unacceptable – Acceptable	0.66	0.20	0.43	0.33
Cheap – Luxurious	0.63	0.39	0.16	0.45
Loud – Quiet	0.59	0.66	0.17	-0.03
Uncomfortable – Comfortable	0.58	0.42	0.22	0.52
Rough – Smooth	0.23	0.86	0.17	0.31
Unexpected – Expected	0.26	0.18	0.91	0.23
Unbalanced – Balanced	0.29	0.15	0.25	0.85

The first principal component (PC1) was most strongly loaded by Noticeable – Unnoticeable, with additional strong loadings from Annoying – Agreeable, Unacceptable – Acceptable, Cheap – Luxurious, Loud – Quiet and Uncomfortable – Comfortable.

PC1 has strong loadings from noticeability, along with variables measuring emotional and environmental factors (agreement, acceptance and luxuriousness), as well as perceived level. This suggests that PC1 represents not only the noticeability of the aeroacoustic sounds, but also how that noticeability affects the experience for the consumer.

It can be helpful to name the principal components for more immediate recognition of the group of variables that each represents, therefore, PC1 is labelled as 'Intrusion'. This component correlates well with the 'Noticeability' category found during the focus group analysis.

Rough – Smooth was the variable that loaded most strongly onto the second principal component (PC2), accompanied by significant loading from Loud – Quiet. Weaker loadings were also provided by variables measuring perceived comfort and luxury. Increases of the psychoacoustic metric roughness can result in an increase in the perceived aggression of a sound [34]. It is proposed that PC2 may be labelled as 'Aggression'; summarising the relationship with both roughness and loudness.

The third principal component (PC3) was strongly loaded by Unexpected – Expected, with minor loadings from variables measuring acceptance. The separation of expectation into mostly its own component suggests that what is expected by a consumer from the aeroacoustic noises, does not necessarily vary in the same way as what the consumer may find intrusive. This component is referred to as 'Expectation', and correlated well with the category labelled 'Consumer Expectation' during the focus group study.

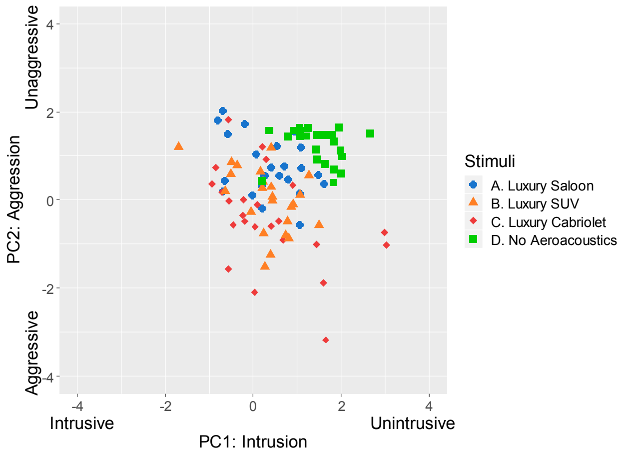
Finally, the fourth component (PC4) was loaded strongly by Unbalanced – Balanced, with minor loadings from a mixture of other variables. For simplicity this component is referred to as 'Balance'; matching exactly the category identified in the focus groups. Since 'balance' in terms of acoustics could describe spatial balance, spectral balance or balance to the other sounds in an environment, the sensitivity of this component to particular stimuli was investigated further.

3.2.2 Analysis of Component Scores

To further explore some of the theories proposed when identifying the principal components, the estimated scores for each participant and for each stimulus were plotted against the new components. During the focus groups it was indicated that only in rare instances do aeroacoustic sounds positively add to an experience. Therefore it is reasonable to assume that due to the deliberate ordering of the semantic pairs into negative and positive respectively, each principal component is positively correlated with a positive measure of aeroacoustic sound quality.

The calculated component scores for the first two principal components, Intrusion and Aggression, can be seen for the vehicle type stimuli group in Figure 6. It is clear that the stimuli with no aeroacoustics active (i.e. only road noise audible), scored more positively than any of the other vehicle aeroacoustic signals for both components. This provides confirmation that a vehicle with no aeroacoustic contribution is perceived as the least intrusive and the least aggressive.

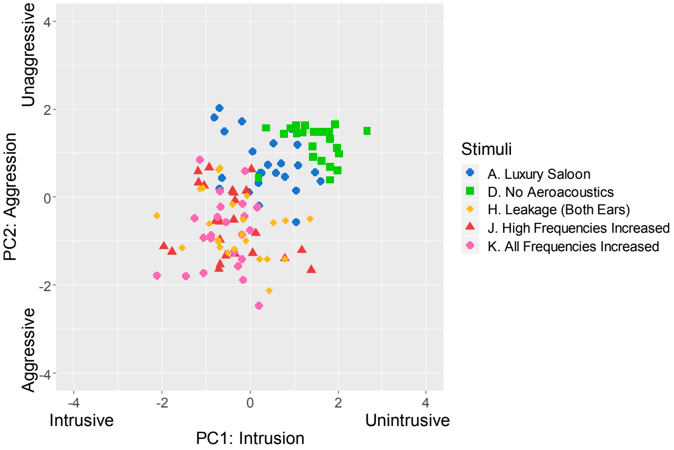
Figure 6



Calculated component scores for Intrusion and Aggression, for the original luxury saloon aeroacoustic signal, the aeroacoustic signal filtered to that of an SUV and cabriolet, and the vehicle with no aeroacoustics active

For the same two components, Figure 7 shows the calculated component scores for the original luxury saloon (A), the vehicle with no aeroacoustics active (D) and three stimuli subject to amplitude increases (H, J and K). It is observed that all three of the 'amplitude increase' stimuli generally suffer penalties for Intrusion; confirming amplitude increases are indeed perceived as more intrusive. Perhaps more interestingly, these three stimuli observe even larger penalties for Aggression, suggesting that this component is sensitive to aeroacoustic leakages and other high frequency amplitude increases.

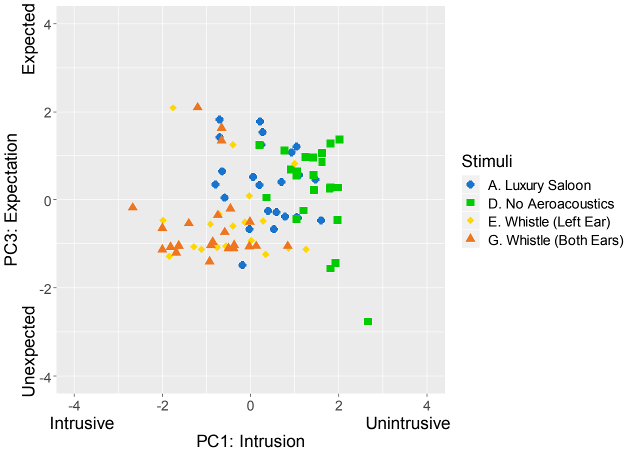
Figure 7



Calculated component scores for Intrusion and Aggression, for the original luxury saloon, the vehicle with no aeroacoustics active and three stimuli subject to amplitude increases

Figure 8 shows for the Intrusion and Expectation components stimuli A and D, and two cases where whistles were added to the aeroacoustic signal (E and G). Intriguingly, it can be seen that despite its higher performance for Intrusion, removal of the aeroacoustic signal is not necessarily any more expected by the consumer than, for instance, the original saloon. It is also shown that faults such as whistles are, generally, not expected by the consumer, and are mostly deemed as more intrusive when compared to the original saloon. It is worth noting that the variation along the Expectation axis is smaller than that seen for the other components, as Expectation was found to explain the least variance.

Figure 8

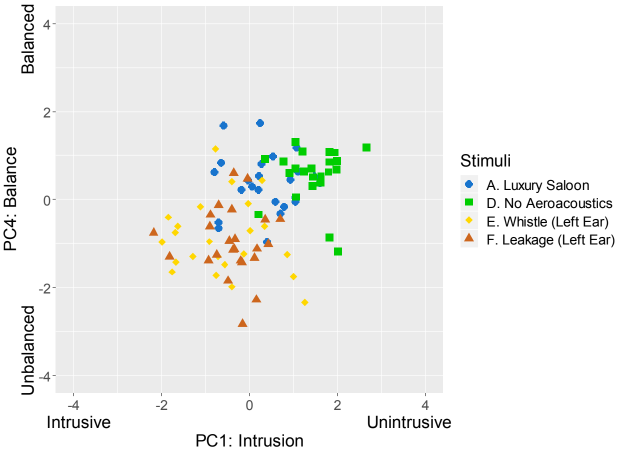


Calculated component scores for Intrusion and Expectation, for the original luxury saloon, the vehicle with no aeroacoustics active and two stimuli with a whistle added to one or both ears

For the Intrusion and Balance components, Figure 9 shows stimuli A, D and E along with a second stimuli which had the aeroacoustic signal manipulated on a single side only. It can be seen that the two stimuli with faults added to the left ear only, generally incurred penalties in the Balance score. This confirms that this component has a relationship with spatial balance.

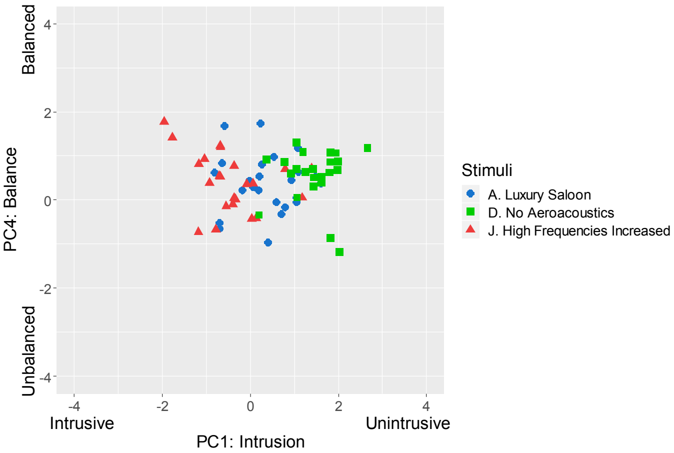
Figure 10 shows stimuli A, D and J for the same two components. Despite the variance in these stimuli along the Intrusion axis, no substantial variance can be seen for Balance; suggesting that PC4 has minimal relationship with spectral balance, or the balance of the aeroacoustic signal to the other vehicle sounds.

Figure 9



Calculated component scores for Intrusion and Balance, for the original luxury saloon, the vehicle with no aeroacoustics active and two stimuli with fault conditions added to the left ear

Figure 10



Calculated component scores for Intrusion and Balance, for the original luxury saloon, the vehicle with no aeroacoustics active and a stimuli with its high frequency content increased

4. Conclusions

Focus group discussions and semantic differential listening studies identified five key factors in the consumer perception of automotive aeroacoustic sound quality:

- Intrusion, related to how noticeable and acceptable the aeroacoustic sounds were perceived to be, was observed to be negatively sensitive to amplitude increases, and positively correlated with the complete removal of aeroacoustic sound;
- Aggression, connected to the perceived roughness and loudness of the aeroacoustic signal; the perception of which was increased with increased high frequency content;
- Expectation, strongly linked to whether the aeroacoustic signal was expected by the consumer, was negatively influenced by faults such as whistles, and is not necessarily correlated with Intrusion;
- Spatial Balance, highly correlated with the perception of balance, was found to be negatively correlated with the addition of aeroacoustic fault conditions such as a whistle or leakage to a single ear position;
- Fatigue, related to how tiring or stimulating the consumer believes the aeroacoustic signal to be, requires further investigation to understand its sensitivities.

Identification of these factors should initiate a change in the methods used by automotive manufacturers to quantify the aeroacoustic performance of a vehicle. Perceived intrusion and spatial balance, or the fulfilment of a consumer's expectation of a sound cannot solely be determined by its spectral shape or psychoacoustic metrics. These factors can only be evaluated with consideration of the spatial representation, the influence of all other vehicle sounds, the environment in which the sounds will be experienced, and the wide range of potential consumers.

Future investigation into automotive aeroacoustic sound quality, could include understanding how the identified key factors vary with transient events such as non-stationary flow conditions, or open apertures. The correlation between the variance of these factors and traditional psychoacoustic metrics could also be explored.

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