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HOW DO AUTOMOTIVE ACOUSTICIANS TALK ABOUT SOUNDS AND COMFORT IN ELECTRIC VEHICLE?

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ABSTRACT

The original idea of this work is to propose an improvement in the acoustic comfort inside electric vehicles, by designing sounds added to sounds perceived as unpleasant thanks to the audio system of the car. The first step in the sound design approach consists in identifying and describing sounds. Therefore, we start by extracting a lexicon spontaneously used by automotive acousticians. The choice was made to conduct 12 interviews guided by a semi-structured questionnaire. The resulting interviews are then analyzed to classify the extracted terms into 4 categories of descriptors formalized in previous studies, illustrated here with examples: Hedonic (e.g. Pleasant), Causal (e.g. Electric motor), Reduced (e.g. High pitched) and Names (e.g. Whining noise). The second step in our framework is to describe the hedonic perception of comfort/discomfort of these sounds using the contextual elements given by the participants. This issue is addressed by obtaining a verbal portrait of the acoustical characteristics perceived as pleasant and unpleasant. We present here the ranking of the most representative sound sources identified in the car cabin as well as their perceptive definitions, focusing on the sound properties and comfort/discomfort impact spontaneously given by participants. The sound design process will be further explored.

Keywords: *Acoustic comfort, Sound Design, Electric vehicle, Interviews*

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1. INTRODUCTION

The automotive industry always had a strong link with acoustic and sound design. Sonic qualities of vehicle are often advertised by the manufacturer [1]. The acoustic signature of 6 or 8 cylinders combustion engines are known to add a luxurious or sportive characteristic to the vehicle. Therefore, these properties were imitated, or ”augmented”, in some thermal vehicle through the audio system with a technology called ESE (Engine Sound Enhancement) [2, 3]. The arrival of the electric vehicle and its relative silence brought a whole new set of questions and perspectives to sound designers and acousticians. The most emblematic example is the design of the AVAS (Acoustic Vehicle Alerting System) to improve pedestrian safety, with the constraint of keeping an ecologic validity of the vehicle's sound [4]. This artificial sound is now mandatory for every new electric vehicle below 30 kmph [UE 540/2014, art. 8]. Another consequence of the vehicle electrification is the emergence of new sounds or sounds that were previously masked by the thermal engine. These sounds could be a source of discomfort for the user. If these sounds can not be reduced, is it possible to develop an augmented acoustic method to improve comfort?

The aim of this work is, first, to identify sounds inside electrical vehicles that have an impact on comfort, and then, to develop an ”augmented acoustic” method based on the description of these sounds to improve comfort through sound design. This paper deals only with the first question. The identification and description of these sounds must be linked with a shared meaning between the different actors of the project to allow a good communication between engineers, researchers and sound composers [5]. Several works were carried to identify methodologies to communicate on sounds in a sound design context with words [6], imitations [7], gestures [8] ... In our work we will focus on the verbal description of sounds. Chion [9] established 3 modalities of description in common language if we exclude quantitative description, imitation and onomatopoeia: causal description, reduced description and contextual description. Causal description refers to the physical origin of the sound and is similar to the "everyday listening" mentioned by Gaver [10], reduced description, first introduced by Schaeffer [11], refers to the properties of the sound independently of the object creating it. Contextual description refers to the functionality of the sound, the context around it or his intention. Contextual description often contains complex formulations such as complete sentences. To build our lexicon, we will only focus on single words related to emotion or judgment, and call this subcategory "hedonic descriptors". This category will enable us to identify the sound characteristic that has an impact on comfort. This 3-level description will also structure the definition formulation for our lexicon.

The definition of comfort is still an open question, it could simply be described as the opposite of discomfort but such a definition proved not to be sufficient [12]. The definition of comfort needs to take into account multiple aspects, from physical measurements to users' expectations [13, 14]. We propose this definition of comfort: "Comfort is a subjective sensation making a manufactured object pleasant in its use and coherent with the users' expectations." highlighting the importance of the expectation and contextual use of a designed object in its comfort evaluation.

Because the literature around sound in the electric car cabin and more precisely its perception is not abundant, we decided to conduct a free verbalization task. This work will involve automotive acousticians that are knowledgeable in the acoustic of the vehicle and its perceptive impact. Thus to explore the vocabulary of the electric vehicle cabin, we follow a method already used in the exploration of soundscapes [15–17] or sound description [18, 19], called the semi-structured questionnaire.

The paper is organized as follows. The first section presents the work that went into the redaction of a semi-structured questionnaire and the interviews conducted. The second section presents the first analysis enabling us to extract a spontaneous lexicon used by acousticians to describe sounds in the electric car cabin. The third part presents the work in progress to formulate definitions of these descriptors and their positive/negative impact on comfort.

2. METHOD

2.1 Semi-structured questionnaire

We decided to conduct our questionnaire through interviews for several reasons. The first one is that we believed this way would enable a more diverse and spontaneous verbalization by the participants [16, 18]. The second reason is that sound description is known to be a difficult task for people that are not used to it [15]. Moreover, we wanted participants to avoid focusing their description on the cause of the sound instead of the perception. Therefore the role of the interviewer was to constantly guide the participant along, to enhance reduced and hedonic description with the causal description they naturally give. The interview methodology was to first let the speaker give a sound description by the cause (Q. 4) and then use the different causes given to help them verbalize and develop the reduced and hedonic aspect while taking care not to induce the participant in saying any concept or vocable he would not have mentioned. This also enables us to obtain technical information needed to reproduce or record specific sounds in the following. The third reason we decided to choose the interview format is to ensure each participant answered these questions in a similar way, within the same time spent.

Our questionnaire is aimed to elicit sound description on the 3 aspects identified causal description, reduced description contextual description. The first part of our questionnaire tackles the issue of sound description and causes.

- Q1. According to you, what big a role does hearing play in your profession?
- Q2. Could you list the sounds you worked on, during the past year?
- Q3. Among the sounds you listed, could you pick up 3 specific sounds?
- Q4. Could you describe the technical origin of these sounds?
- Q5. Could you now describe the sound itself, focusing on the sounds properties and not referring to the cause?
- Q6. After our discussion, do you see any additional words you did not mention?

The second part asks questions about the components that have an impact on comfort. The questions here closely converge toward the notion of augmented acoustic and sound design.

- Q7. According to you, what place does sound comfort has in your profession?
- Q8. How would you define it?
- Q9. Is there any specific sound in the car cabin you would qualify as uncomfortable? Comfortable?
- Q10. Would we be able to design a sound played by the audio system of the car that would correct the uncomfortable property identified?

2.2 Participants

We selected a list of 15 potential participants for our semi-structured interviews among Renault's acousticians based on their experience on electric vehicles and automotive acoustics. We contacted each of these participants in the same way, by sending a first e-mail presenting the global topic and asking if they would volunteer in this study. A 20 minute phone call gave afterward further details on the subject and answered the potential questions. These 20 minute phone calls were also useful to build the relationship suggested by Tardieu [16] to carry an interview. Among the 15 people approached, 12 volunteered to take part in the study (3 females, 9 males) , with 5 to 26 years experience in automotive acoustics (with an average of 17 years). All participants reported a regular use of electric vehicles.

2.3 First results

The whole interview was set to last 1 hour, the shortest was 45 minutes long and the longest 1 hour, 32 minutes (with an average of 1 hour, 12 minutes). The first 2 participants were interviewed a few weeks before the others and were selected for their more extensive knowledge on the subject. We took the time to discuss the clarity of every question and the general feeling of the interview before interviewing the other ten participants. Minor modifications were made following these 2 interviews. The first was to avoid complex terms such as ”causal”, ”hedonic” or ”reduced” in the questions and rather use periphrases to explain these notions. The second modification is that we added systematical questions asking for example of sounds that can depict these discussed characteristic. In the following, all 12 interviews are considered identical. Each of the interviews were recorded and transcribed for the further analysis. The participant approval for the recording was explicitly asked before the interview and recorded at the beginning of the discussion. The interviews were led both remotely (33%) and face-to-face (66%); face-to-face were easier to lead and last 15 minutes less than remotely in average (1h08 vs 1h23). This difference might be explained by the difficulty to speak simultaneously during the exchange and the lack of non verbal communication in the case of video call. Apart this, no noticeable differences were observed between the 2 modalities.

3. ANALYSIS

3.1 Word classification

A 4th category is added To the 3 categories previously identified, which is a subcategory of the causal description: ”Sound Names”, that is useful to accurately identify a sound by the name commonly used by the participants. In the following, we will mainly focus on 3 categories: ”Names”, ”Hedonic descriptor” and ”Reduced descriptor”, because the sound names category is included in the causal category but is more likely to include single word descriptors, which will be treated more easily in the following. This categorization has been manually performed by the author based on the written transcription of each of the interviews. We now have a set of words stored as a table (Table 1).

Table 1: Overview of the different descriptors classified in the 4 categories identified (Name, Causal, Hedonic, Reduced), with a namecode for each sentence.

Namecode	Names	Causal	Hedonic	Reduced
MDs01	*Name1*		*Hedo1*	*Reduced1*
PBs12	*Name2*	*Cause1*		
PBs53	*Name3*			
...				

3.2 Descriptor ranking

The first step of the categorization enables us to extract the candidate words for our lexicon and classify them. The second step aims at identifying the key words by ranking them. To do so we explore two methodologies (Fig

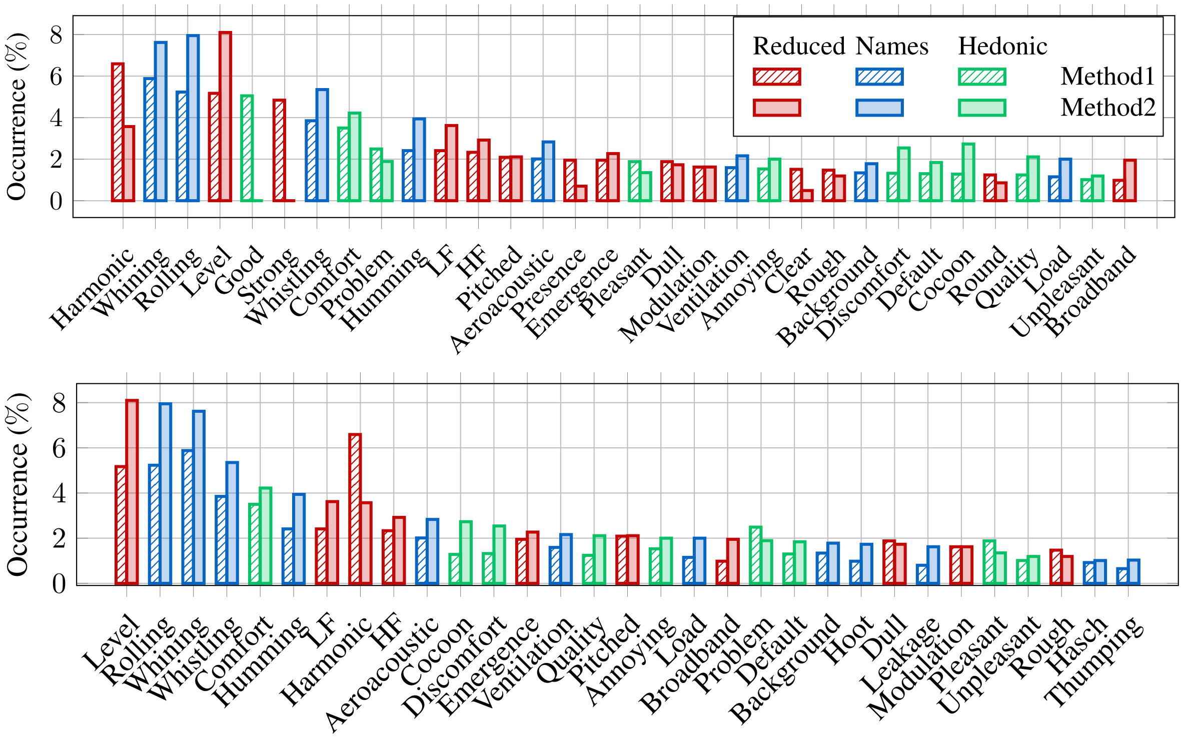

Figure 1: Histogram comparing the descriptor occurrences with word frequency (Method1) analysis and Leximancer (Method2). The top figure is ranked by word frequency and contains 83% of word occurrences and the bottom figure is ranked by concept frequency in Leximancer and contains 87% of concept occurrences.

1). The first one is the more natural one: word frequency analysis. We first achieved a stemming of the words previously classified, therefore adjectives (e.g. strong), adverbs (e.g. strongly), comparatives (e.g. stronger) and superlatives (e.g. strongest) will be reduced to the root (e.g. strong-) and treated as a unique descriptor. We had concerns about the biases this methodology might have: first, the format of the interviews might incite participant or the interviewer to repeat a word for clarification purposes, increasing its frequency, whereas a unambiguous descriptor might be pronounced a single time. The second bias that is inherent to this methodology is the lack of differentiation between synonyms ("Bass" and "Low Frequency") that would be considered as 2 different descriptors. We thus decided to explore a more automatic analysis trough a known text analysis software: Leximancer. This software is known to be based not only on word frequency but also on co-occurrence of words. Leximancer identify *Concepts* among a list of *Seeds*. *Seeds* are automatically identified among the words appearing the most frequently in the text or the words in a list provided by the user. *Concepts* are identified by clustering seeds together depending on a weighting function based on 2 parameters: the cross-correlation of these seeds and the distance they have in the text. Once the *Concepts* are identified, they can be ranked and rated by applying a data reduction method on the correlation matrix of the different concepts identified in the text [20, 21]. Leximancer then produces a concept map, illustrating the link identified between concepts (Fig. 2).

Leximancer suggests default settings values to perform the analysis depending on the text size and type. The only parameter we changed was a concept seed identification parameter by choosing 'Total Number of concepts=100' and 'percentage of name like concept =70 %' which is significantly higher than the default value recommended. This difference is explained because we will create a large quantity of Name-Like concepts. Name-Like concepts are detected among seeds starting with a capital letter; we thus provide a seed list by turning every descriptors previously identified Fig. 1 into a Name-Like concept

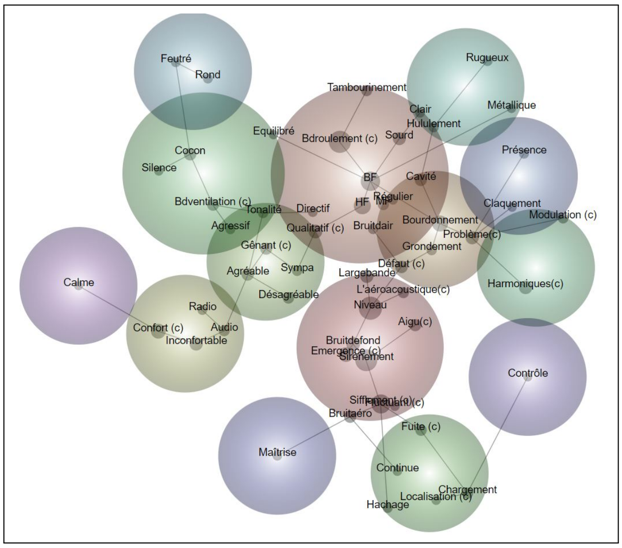

Figure 2: Concept map output by Leximancer. Concepts are represented by nodes and clustered as "Themes" depending on the distance computed between concepts, materialized by the bubbles. Nodes are bigger when the concept is more important in the data set.

(*High, Low, Pleasant...*). Leximancer will also identify concepts by itself (30 %), but none of the self identified concepts were used in the following. We also kept the 'Dialog Tag ON 'to identify the speakers but did not use this functionality and made no difference between speakers, including the interviewer. This way the Leximancer analysis will use the complete text with the default parameters to rank and identify the concepts we highlighted with a capital letter.

3.3 Comparison of the different rankings

We plot in Fig 1. the first 33 descriptors from the word frequency analysis and the concept analysis of Leximancer, Fig. 3 and Fig. 4 give the result for the sound names and reduced category. Because the values of concept occurrences and word occurrences cannot be meaningfully compared, we instead compare the occurrence percentage descriptors have. We first rank the same dataset of descriptors by word frequencies (top figure) then by concept occurrence (bottom figure). This way, we can easily highlight the difference in behavior.

The interviews were carried in French, each word has been translated into English with Deepl and the associated bilingual concordance tool, Linguee. The only descriptor that did not followed this protocol is "whining" (*sirènement*) this name have already been identified in the industry and academic field and called "whining noise" or "whine noise". The translation offered by the mentioned tool was not satisfactory and did not fit this. The causal description of the sounds given by the participant could ensure this English word do correspond to the same sound.

We can identify descriptors getting different values depending on the method. "*Good*" and "*Strong*" are the most blatant examples. "*Good*" is considered as irrelevant to Leximancer because it is a stop word, especially in French where it is very often used in oral expressions to signify a conclusion or transition. On the other hand, the word "*Strong*" is not identified as relevant because of his high correlation and low distance with the word "*Level*" in its use, therefore these 2 words have been automatically merged in the more global "*Level*" concept. This might also explain the difference of percentage between the concept "*Level*" and the occurrence frequency of the word "*Level*". Another example very tricky for both methods in our analysis is the descriptor "*Harmonic*". This descriptor is either used as an adjective or noun, and the adjective might have different meanings depending on the context. Based on the author observation during the interviews, the noun "*Harmonic*" is often used in the same meaning as "*Tone*". The adjective, on the other hand, is either used to refer to its mathematical meaning, i.e. a sound composed of a fundamental frequency f_0 and frequencies f_i multiple of the fundamental, or used to describe the link between the pitch of a sound with the rotation speed of an element: the complete formulation would be "motor rotation harmonic" (electric motor, compressor, gears...) but abbreviated "harmonic". Some sounds could be described as "harmonic" because the pitch is proportional to the rotation speed of the engine, despite that at any given rotations per minutes the spectrum does not show harmonic behavior.

To build our lexicon we will take the basis of the 13 first sound names identified by Leximancer (Fig.3). These 13 descriptors represent more than 90 % of the words and concepts identified as sound names.

4. SOUND DEFINITION

The aim of this section is to present the methodology explored to formulate definitions for the names descriptors identified in the previous section and its first results.

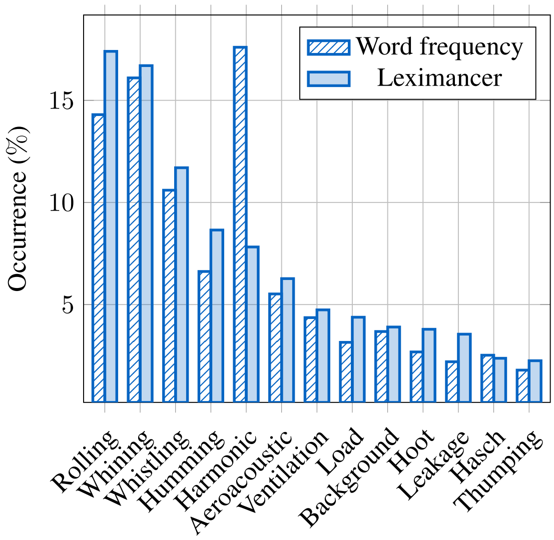

Figure 3: List of the sound names descriptors used in the following. We ranked the descriptors following the Leximancer concepts occurrence and kept the word frequency values to enable comparison. 93% of concept occurrences are represented and 91% of word occurrences related to sound names.

4.1 Methodology

We explore a 3-step methodology to propose a perceptive definition and give a verbal portrait of the different sounds identified. We formed a grouping work of 3 members, including 3 authors. This jury does not have any specific experience on automotive but do have a knowledge on sound design and perception. For each sound this jury will perform the following tasks:

- The main author establish the list of hedonic and reduced descriptors previously identified Fig. 1 used by each of the participants and extract the specific audio of the interviews describing the sound.
- With these 2 documents (the list and the audio), members of the jury provide their own definition of the described sound and a ranked list of the most relevant descriptors. The definition should have one sentence referring to the causal description of the sound, one for the reduced aspect and a last one for hedonic aspect.
- Definitions are then merged together. The experts, who took part in the interviews and mentioned the sound, are solicited to assess if the definition is relevant.

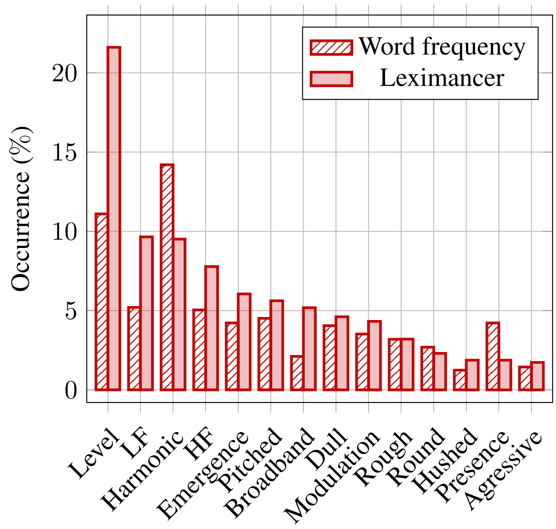

Figure 4: List of the reduced descriptors used. We ranked the descriptors following the Leximancer concepts occurrence. 85% of concept occurrence are represented and 67% of word occurrences related to reduced description.

Let us give an example, translated from French: Hoot (*Hululement*): Cavity mode, of a tyre around 80 km/h for instance, produces a sound also called "Hoot". It corresponds to two near low frequency lines, in low frequency ($\approx$ 200 Hz), with a fast amplitude modulation rate ($\approx$10 Hz) very similar to a beating. Its emergence ($\approx$6 dB) in comparison with a broadband noise (rolling) makes it identifiable. This sound is constant in frequency, amplitude and modulation velocity, which makes it exhausting.

The work in progress consists in illustrating definitions with examples containing sounds. The complete lexicon could then be presented online on the SpeaK platform `https://speak.ircam.fr/` [22].

5. CONCLUSION AND PERSPECTIVES

We explored a methodology to extract a meaningful list of words to describe a specific sound environment, the electric car cabin, which do not benefit a wide literature or user's community because of its novelty, originality or specificity. This list of words is then used to build a full lexicon, including definitions and sound examples, where the descriptors used have been identified through a text analyzer on a free verbalization task: a semi directive questionnaire. We compared 2 different text analysis methodologies: a classical word frequency and an automated one, Leximancer. The limitations of both methods are illustrated by several examples. The first one are descriptors such as ”Harmonic”, where the meaning of this word strongly depend on the context, for instance if it is used as a name or adjective. A second are descriptors such as ”Strong” and ”Level” are strongly correlated in their usage. A last example are descriptors not mentioned earlier such as ”Rough” or ”Smooth” that could either describe a sound or road surface. Even if such descriptors are identified by our analysis, there is a legitimate doubt on the relevance for a lexicon describing sounds, a doubt which can not be satisfactorily erased by either method. Identifying the right descriptors to represent a sound environment still requires a human action. We decided to reduce this human intervention to the formulation of a definition through a jury composed of 3 people working on sound perception, followed by a validation by the automotive experts. This gives us a first a posteriori comparison of the reduced descriptors used by the jury and identified by the text analysis.

Following this, several perspectives appears. First, finalize the lexicon by completing the work in progress on definition and sound illustration. Second, design augmented sounds that would modify the perception of an environment and making the atmosphere more comfortable. To achieve this, the lexicon will help identify the most critical aspects of the sound and how to treat them. The first step will be to replicate sounds and their reduced characteristics identified in the definition formulation, before being able to augment some of their properties. A third perspective could be to use this lexicon to obtain verbal portraits of specific target atmospheres, already identified in the car industry, that would give a sound description for a sound design.

6. ACKNOWLEDGMENTS

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