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The influence of vibrations on perceptual sound attributes: Application to Diesel vehicles

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A mamie.

“When I hear your 12 cylinders,
I hear a burst of harmony no conductor could ever recreate”.

Herbert von Karajan to Enzo Ferrari

Résumé

Dans cette thèse, nous nous attachons à étudier l'influence des vibrations siège et volant sur la perception sonore des véhicules Diesel et à en extraire des caractéristiques dites *positives*, liées à la préférence. Aussi, en plus de cette approche multimodale, la question interculturelle est abordée entre la France et l'Allemagne afin d'étudier le jugement des utilisateurs de ces deux pays d'Europe fortement diésélisés. La caractérisation de cette source Diesel passe, en premier lieu, par la définition de ce qui est Diesel dans le fonctionnement du véhicule. La première expérience menée dans ce travail, sur la base d'un corpus de différents sons de véhicules Diesel, permet d'y répondre. Autant pour les français que pour allemands, les situations de conduite considérées comme les plus représentatives de la sonorité d'un véhicule Diesel sont le ralenti et l'accélération. En se focalisant donc sur chacune de ces deux situations, leur espace sonore révèle des caractéristiques connues et nouvelles. En effet, les ralentis de différents Diesel se différencient par leur fréquence de modulation et sont dépréciés en présence d'une forte modulation. D'ailleurs, cette dimension se caractérise par un découpage précis des véhicules suivant leur appartenance à une gamme. Aussi, d'autres paramètres acoustiques permettent de les différencier suivant la deuxième dimension de l'espace sonore. Concernant l'accélération, les différentes sonies instationnaires N5, N10 et STLmax distinguent à l'ordre 1 les quinze véhicules présentés. De la même manière que pour le ralenti, la deuxième dimension de l'espace sonore est approximée par une combinaison linéaire de plusieurs descripteurs. Grâce à ces résultats, nous validons ceux discutés dans le domaine par la communauté scientifique, avec une approche multidimensionnelle. Enfin, l'influence des vibrations du siège et du volant sur la perception sonore du caractère Diesel et sur l'espace sonore multidimensionnel obtenu est abordée. Dans le premier cas, à part une sévérité un peu plus marquée chez les allemands, les résultats ne montrent aucun impact significatif de cette modalité sur la perception du caractère Diesel. Le ralenti et l'accélération sont toujours considérés comme les situations de conduite les plus représentatives de ce caractère. Dans le deuxième cas, là encore, leur influence n'est pas notable : l'espace sonore et la préférence ne s'en trouvent pas modifiés. La reconnaissance et l'appréciation hédonique d'un véhicule Diesel passent donc avant tout par la composante acoustique de celui-ci. Ces résultats vont donc contribuer à continuer dans la voie de la qualité sonore pour faire du son Diesel un son apprécié.

Abstract

In this thesis work we focus on the influence of seat and steering wheel vibrations on the sound perception of Diesel vehicles, and we try to extract *positive* characteristics, related to the preference rating. In addition to this multimodal approach, the cross-cultural question between France and Germany is investigated to compare user judgments between two European countries which use many Diesel cars. The characterization of the Diesel source can be initially done by defining what Diesel is during the vehicle's operating state. The first experiment of this work answers this question based on a corpus of various Diesel vehicles. The driving situations which best represent the sound of a Diesel car are hot idle and acceleration for both French and German people. Therefore the sound space for these two driving situations reveals known and new features. Indeed, various Diesel vehicles in hot idle are distinguished by their modulation frequency and people depreciate those with strong modulation. Moreover, this dimension is characterized by groups of vehicles which belong to the same car classification. Also, other acoustic parameters distinguish the vehicles along the second sound space dimension. Concerning the acceleration condition, the different unsteady loudness N5, N10 and STLmax distinguish the fifteen vehicles at order 1. In the same way as for the hot idle condition, the second dimension can be approximated by a linear combination of several descriptors. Thus, we can validate data discussed in the field by the scientific community with a multidimensional approach given these results. Finally, the influence of seat and steering wheel vibrations on the sound perception of Dieselness and on the multidimensional sound space obtained is discussed. For the first case, the results show no significant impact of this modality on the Dieselness perception except for a slightly greater severity in Germany. The hot idle and acceleration conditions are still considered to be the most representative of that feature. In the second case, their influence is still not significant; both the sound space and preference are not altered. The recognition and the hedonic appraisal of a Diesel car mainly come from its acoustic component. These results will contribute to the improvement of the Diesel sounds as to make it an appreciated sound.

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Introduction

The development of new engines is a strong challenge for the automotive industry. In recent years technological advances have increased their overall performance thanks to the improvement of consumption, pollution and noise level. However, new and future European antipollution regulations, such as Euro V in 2010 and Euro VI in 2014, could impact the sound of Diesel motorizations, thus potentially degrading engine noise performance through the emergence of other noises. But today it is obvious that the interior noise has become an argument put forward by manufacturers and it is consistently noticed by the specialized press.

The historical use of Diesel motorizations for mostly agricultural and industrial purposes does not give them a positive image. Regardless of this perception, their direct competitor, the gasoline engine, is fading. Improvements made on their sounds, performance, pollution or vibrations, for instance, allows one to start speaking about Diesel sound, not Diesel noise. Moreover, this notion allows the introduction of pleasure associated with the sound of Diesel vehicles. The future of Diesel sound should not simply copy the gasoline sound, rather, it should find its own personality on which the user can place his or her imagination. It is no longer sufficient to remove the most obvious defects and hope to provide an "acceptable" sound. Apparently, the improvements of the last decade have brought Diesel vehicles to a necessary basis in order to initiate sound design process. But what are the recognition of features of Diesel cars and how to get a sound in adequacy to users' expectations? There will always be the fiercest defenders of one engine or other one with valid arguments depending on sensitivity of individual.

In order to work on this sound design, two preliminary goals must be reached: the sources' identification and their characterization. As it has already precised before, improvements on Diesel engines allow to localize even to eliminate the main defects. Therefore, the remaining task is to characterize these sources through the characterization of Diesel as a whole.

However, at first, qualifying the Diesel sound is a titanic task. What is Diesel? How to characterize it? Where to start? The solution has been found by first answering the question *"when do you recognize the Diesel sound?"* Indeed, this question constitutes the basis of this thesis. Determining the moment at which one can recognize that he or she is driving a Diesel car, allows to clarify the rest of the study. In order to reach the work's objective, four problems are posed (and detailed in Chapter 1):

- When can one recognize Diesel character?
- Which sound attributes are typical for Diesel driving situations?
- What is the influence of vibrations on Dieselness perception?
- What is the influence of vibrations on Dieselness sound attributes?

Besides, this thesis work focuses on a multimodal approach (with sounds and vibrations) and a multicultural approach, between France and Germany. The motivations are demonstrated in Chapter 1.

Chapter 1 starts with the presentation of automotive and scientific contexts in order to expose the industrial and scientific expectations on the Diesel sound. Subsequent chapters are divided into two parts: theoretical and experimental.

Chapter 2 and Chapter 3 tackle Diesel engines in two ways. Chapter 2 introduces the Diesel vehicle and its functioning's noises. While in use, a thermal vehicle, particularly *the* Diesel, produces many noises. Between the noises of the engine, road and wind along with those caused by vibrations and various others generated by the user himself or herself (direction indicators, horn or windshield glass), Diesel is clearly a complex sound source. The non-exhaustive list of noises in this chapter highlights those which contribute to the global noise of the engine perceived in the cabin. Chapter 3 presents the subjective approach regarding the perception of sound and vibrations. By introducing perception's notion and the general subjectivity linked to it, we continue then with techniques developed in this domain (paragraph 3.2) to "measure" this subjectivity.

The second part, dedicated to experimental work, starts with Chapter 4 in which measurements of sound and vibrations inside vehicles are presented. As different campaigns of recordings have created a sufficient sound and vibration database, Chapter 4 summarizes not only the methodology of these recordings but also sound and vibration reproduction setups.

With the four remaining chapters (Chapter 5 to Chapter 8), we answer each intermediate problems detailed in Chapter 1 with paragraphs 1.3.1, 1.3.2, 1.3.3 and 1.3.4. Chapter 5 presents sound driving situations which best represent Diesel character prior to describing their relative sound attributes in Chapter 6. Similarly, influence of the vibration modality parameter is studied on Diesel character in Chapter 7 and on its sound attributes in Chapter 8.

Finally, during the different experiments, an intercultural study between France and Germany has been realized on Diesel character's perception. Therefore, for sound and vibroacoustics appraisals of Dieselness (Chapters 5 and 7), a discussion between results obtained by these two populations is presented.

During this thesis work, at least one experiment has been performed in each institution which has supervised this work (Renault, IRCAM and Oldenburg).

Chapter 1

Context of the study

The history of Diesel engines does not give them a positive image. However, the improvements on performance, pollution or noise makes one start to speak of the "Diesel sound" and not just the "Diesel noise". Besides, they have contributed to the strong break-through of Diesel in the European market. However, the market share gained by this type of motorization may, in the future, be impacted by European regulations. Indeed, these standards, which concern reduction of polluting gases emissions, can impact on the one hand, the cost and on the other hand, the sound of Diesel engines thus significantly degrading their acoustic performance. Moreover, in an eco-citizen approach, development and emergence on the world market of electric vehicles appear as a direct competitor to Diesel.

In view of the progress already made, the future of the Diesel sound is to acquire its own personality. Can we imagine the sound of Diesel engines outside of its historical context? Should we consider a Diesel sound based on new criteria such as ecological, clean or sporty engine? Furthermore, another more marketing approach thinks about sound, like a potential representative of the brand.

The amount of work from the scientific community in understanding Diesel noise perception is a consequence, specifically for the idle situation. Combustion noise, considered as the main drawback of these engines, is largely tackled. This defect, now better controlled, is regularly presented in international congress and is greeted by the press. However, most of the bibliographic elements are focusing on quantification and elimination of this defect. In this thesis work, we want to free ourselves from this manner and contribute to the knowledge of this daily-life sound with an approach of *sound space* (to characterize the Diesel sound attributes). Moreover, we will take into account a second modality: vibrations and their influence on Diesel perception.

This first chapter introduces the framework on which the thesis is based with two approaches: the automotive one (paragraph 1.1) and the scientific one (paragraph 1.2) before finishing with a presentation of the structure of the document with four axes of work (paragraph 1.3).

1.1 Automotive framework

After the revolution provoked by the automobile's appearance at the beginning of the last century, the global car fleet is assessed at over one billion today. From an object of lust to a most common object, the car has become a product whose technical performances are almost due, according to the client. The function of a car is not limited to move people from point A to point B anymore. Its primary function of "useful consumption" is no longer valid.

The vehicle's sound is also a vast subject, mainly, the one of the Diesel car. The sound evolution of this kind of vehicle takes part in restoring its image. Indeed, the automotive industry has worked hard to detect, contain and eliminate the defects inherent to the functioning of Diesel. Today, the work's approach on this type of car has joined the requirement of gasoline ones by focusing on comfort or pleasure, and even, sportivity.

In this automotive part, we will introduce in the first paragraph the Diesel car and its evolution before tackling the one for whom all is thought: the user.

1.1.1 Diesel engine: heart of this work

Diesel is a strong stake for European automotive industries, especially in France. Indeed, in its 2010 annual publication, French Car Manufacturers Committee sums up Diesel development in France. Since 2002, registrations of passenger cars equipped with Diesel engines were superior to those equipped with other engines. In 1997, the market share of Diesel vehicles was 25% but reached nearly 50% in 2005[1]. In 2009, it represents 71% of total registrations with France and Germany leading the European market for this kind of motorizations. The new Diesel motors more sober and more competitive, still raise a real craze.

However, the main reason for a Diesel vehicle purchase remains economical [10]. If it has the advantage of being recognized for this, it presents today some acceptable noise level but still not appreciated, despite projects undertaken on the annoyance of Diesel noise [11] [12] [13] [14]. Criticisms concerning it, appear less severe, but the image linked to agriculture, to industry and to noise, sticks to the skin[2]. Unlike the gasoline engine which has a strong emotional context ("more nervous", "less noisy", "driving pleasure"), the history of Diesel vehicles does not have the prestige of famous racing models. Indeed, 75% of people, having a gasoline vehicle answered in 2008 [10] that "driving is often a pleasure", while only 62% of those having a Diesel vehicle answer the same thing. Saint-Loubry [15] who worked on the sound of gasoline engines highlights a paradigm. "Sound" and "noise" represent one same concept related to the sound perception. "Sound" appears as a term, holder of aesthetic qualities, meanings and, values in a positive context, often used for gasoline engines. Rather "noise" is used to characterize a sound without expression by the listener with little attempt to describe it except in negative terms and, is often used for Diesel engines[3].

Therefore, in the light of technical progress, the future of the Diesel sound is to acquire its own personality. The working approach developed here, exceeds the stage of identifying the defects in having a *positive approach* to describe Diesel sound while forgetting rooted prejudices. This work approach is quite new (for the Diesel engine) because totally different studies realized in scientific literature, which focused on impulsive character of Diesel sound [16] [17] [18], named the characteristic, Dieselness [19] [20].

1.1.2 User: last "link" of the automotive industry

If perception (paragraph 3.1 p 29) comes under each individual, its control in industrial settings fits into the main problem of human-centered design. Indeed, the noise generated by the use of a product reflects its quality and plays a significant role in the purchase decision. Perceptive studies of vehicle noise is motivated by the desire to satisfy customer's expectations.

A Diesel user is now familiar with the idea that his engine is no longer as noisy as the engine of a commercial vehicle or of a farm machinery, and he does not want to go back. And even if the interior noise

[1] Le Magazine de la Recherche et du Développement, $n°$ 38, 2005.

[2] First Diesel engines have been integrated into ships. Indeed, first models of this motorization were too heavy and too big to be placed in vehicles. Its rapid spread is related to its increasing use in railway in the United States. It is only in the 30s' that they appear in automotive field with bus and trucks (http://www.motorlegend.com).

[3] In the following of this document, I will use indifferently "sound" and "noise" terms in a neutral manner to evoke the Diesel.

has not yet become a purchase criterion, Saint-Loubry [15] specifies that it is a good reason of non-purchasing. The interior comfort is becoming important for people and a survey realized at Renault helps to highlight their overall expectations in terms of sound quality. Among these expectations, the noise is at the foreground. Particularly, inside the vehicle (especially at idle) and outside the vehicle for small vehicles and those in UK and France where they desire to escape to the social stigmatization (*"it is spotted from kilometers", "it sounds like teuf-teuf"*). Moreover, the Group Diesel - Sound Quality [21] summarizes clients' expectations of Diesel sound, in three criteria of quality:

- comfort: with noise controlled, in city or highway situations. The acoustics must be close to a muffled, sober, low-pitched and warm sound in order to contribute to a reassuring sound;
- reliability: the safety of functioning at idle without Diesel knock, like castanets, and irregularities,
- power in reserve: related to the quality of mechanics with a "brilliant" sound.

Overall, this study concludes that the Diesel vehicle is perceived as a car made for long-distance trips, a quiet strength. This identity, that distinguishes Diesel cars from gasoline ones, must be translated by a sound more mature, more sober and more disciplined. This Committee helps to provide further informations about Diesel users: we can classify them into four categories (cocoon, fusion, escape and control). Each of these categories refers to a particular driver:

- cocoon for the one who wants to hear nothing in his car,
- fusion for the one with an overly close relationship with his vehicle, mainly sporty client,
- escape for the one who considers his vehicle as a mean to escape the daily-life,
- and control for the one who often needs to hear road noise in order to have information about grip and behavior of the vehicle.

Various internal investigations confirm the customer's expectations concerning the noise: 50% of polled people attach a great importance to the sound inside their vehicle [10]. In 2002, 25% of customers complained about the noise of their vehicles which represented their first reason of dissatisfaction.

Last link in the chain, the user appearing as a demanding client. Subjectivity, proper to the individual, is central to this study, especially in the case of industrial application for which all upstream choices have to meet customers' expectations.

1.2 Scientific framework

This study is interested in a daily-life urban environment sound that all people know (even children for whom, the first imitations of vehicles summarize to *"vroum-vroum"*). Throughout this study, we are focused on a sound anchored in the subconscious of all. However, we ask people to make some effort in order to concentrate on this sound and even to evaluate it where they "do not hear it anymore" [22] (except when problems of functioning appear).

Therefore, this study allows one to define the sound attributes of this complex source, with a *sound space* (defined and described in Chapter 6). Explaining the feeling and the judgment of people by understanding physical phenomena represents the basis of all subjective scientific works. Thanks to this, we free ourselves from the research of defects and focus on the idea to "find" *positive charateristics* of Diesel (if they exist). The ultimate goal would be to define an "ideal" Diesel sound, but does it exist? As for all "ideal" approaches, it seems to be difficult to settle this question since, by definition, the subjectivity is proper to each individual. However, the *sound space* study of this motorization can allow us to bring some answers because until now, none of previous studies have focused on Diesel issues in this manner. Since a Diesel vehicle is a complex source, a multimodal aspect is also dealt with. Indeed, Diesel cars are known to vibrate more than gasoline ones: it is so inconceivable to work without vibrations [23].

In this scientific part, the interdisciplinary of this study is demonstrated by tackling multimodal and intercultural approaches. In addition, we explain what innovation this study brings.

1.2.1 An interdisciplinary context

One of this topic's motivations resides in its interdisciplinary aspect with two approaches: more broadly with the exploration of various scientific domains and more precisely through different work approaches. First, with this PhD work, fields like Fundamental Sciences with Physics, Acoustics, Signal Processing, Statistics or Vibrations and others from Humanities and Social Sciences with Perception, Psychacoustics, Cognition or tests' methodologies have allowed a transversal approach of this topic. Indeed, each of these disciplines represents a vast research area but the goal of this work was not to go deep into them. Making good use of well-known techniques from various fields in order to apply them to the automotive domain and allow their complement in this project: this is the interest of this multidisciplinary approach. Secondly, the collaboration between a firm and scientific institutions allows one to take into account expectations of each team. Indeed, this study has been sustained by teams from Renault[4], IRCAM[5] and Oldenburg University[6].

This interdisciplinary context comes down to two points: a vibroacoustic and intercultural perceptive study. Indeed, by starting to work on the vast subject of Diesel vehicles, two preliminary experiments have been performed in order to first answer: what people think about exterior and interior noise of Diesel vehicles [10] and how do they perceive the market's varied offer of Diesel vehicles [24]?

First, I proposed in 2008 a questionnaire [10] to thirty-two participants in order to collect information about the collective thought on Diesel cars. Nineteen opened and closed questions on *interior* and *exterior* noise of Diesel cars were asked. As we supposed that it is difficult to speak of Diesel with positive terms, we asked questions about what was unpleasant about Diesel sound, but we especially "forced" them to say what was pleasant too. The instruction of this questionnaire can be consulted in Appendix A. The main results revealed were:

- among the four drivers of gasoline vehicles, three of them bought it for economical reasons and the last one for a bad image of Diesel vehicles (*"noise", "vibrations" and "black smoke"*);
- 16% of participants attached little importance to *interior* sound of a vehicle, 34% a certain importance and 50% attached a great importance;
- one of the participants (answering to *interior* sound questions) described the *"vibrations"* which participate to the unpleasant interior acoustics;
- 28% of participants attached little importance to *exterior* sound of a vehicle, 41% a certain importance and 25% a great importance;
- another participant expressed, here that, the *"vibrations"* were unpleasant to the exterior acoustics.

Secondly, with an experiment of classification [24], eight sounds of accelerations (of four kinds of Diesel vehicles with 3, 4, 5 and 6 cylinders) were presented to fifty-one participants. Results of this experiment allowed the collection of many verbalizations produced by each person in order to explain their different clusters. The instruction of this classification experiment can be consulted in Appendix B. The main conclusions of this test revealed that:

- people managed to group together vehicles of the same classification[7] and therefore, with the same cylinder's geometry (*i.e.* the number of cylinders into the engine);
- each of clusters was associated with a particular category of verbalizations. For upper class vehicles, the majority of verbalizations belonged to hedonic judgments (*"pleasant"*, *"soft"*) whereas for cars of lower classification, *"Diesel"*, *"vibrations"*, *"noisy"* or still *"truck"* were associated to them.

The last conclusion tends to prove the people's spontaneity to evoke *vibrations* during a listening test (with a sound reproduction by loudspeakers).

This preliminary stage of results allowed to propose two work axes: keep vehicles of different classifications and develop multimodal experiments with sound *and* vibrations in order to validate the evocation of vibrations for 3-cylinder cars more particularly. In literature, studies led on interactions between sound and

[4] Mechanics, Fluid, Vibrations and Acoustics Group of Research Department, Guyancourt, France.
[5] Perception and Sound Design team, Paris, France.
[6] Acoustics Group of Physics Institute, Oldenburg, Germany.
[7] Lower, Middle and Upper classifications.

vibrations in the automotive domain have been mainly limited to the study of idle [25], comfort issues [26] and rarely, the influence of engine's geometry [27]. The multimodal approach seems essential because it is directly linked to the perception of the passengers in the cabin.

Moreover, a cultural parameter has been integrated into this topic. Do perceptual differences exist between two European populations (French and German), known as being two countries which possess the most Diesel vehicles in their respective markets (cf paragraph 1.1.1) [28] [29]? If yes, what are the perceptual differences between those countries? Previous studies on intercultural differences have already been realized more particularly between Europe, America and Asia which have shown some differences between those different continents [30] [31] [32] [33]. But what happens between two countries on the same continent? To answer to this question, several experiments realized during this thesis have been performed in both countries. Our hypothesis about cultural difference does not expect to find big differences between the two populations.

1.2.2 The Diesel sound: a *positive* approach

As it has already precised before, car manufacturers have improved their vehicles' models by working hard to eliminate the typical Diesel sound or, of course, parasitic sounds which give bad image to this kind of motorization. This present work focuses on another manner to tackle Diesel features that I could qualify as a *positive approach*. Indeed, until now the reduction of noise level or of the knock has represented a "positive" method with the intention of improving passengers' comfort. However, by using the *positive approach* expression, I want to refer to something stronger: to think about Diesel in a positive manner, forget its farm history that sticks to its skin and above all find its positive characteristics. This axis of work will result in the elaboration of Diesel *sound space* by showing preferences of participants in this space in order to explain *what is positive* about Diesel sound and even *what brings the sensation of pleasure*.

Moreover, this approach does not only summarize in this way. In fact, the *sound space* issue of Dieselness in a multimodal approach (with sound and vibrations) constitutes two original other aspects of this work. Concerning the first one, the various studies realized on *sound space* (or on timbres' space especially in the musical domain) have treated other kinds of stimuli (musical ones [34] [35] [36], air-conditioning sources [37] [38] or different automotive sounds [39] [40] [41] [42]). None of them have focused on Dieselness perception. As we will see in Chapter 6, *sound space* has been built for the driving situations which were revealed representative of Diesel for people. Keep in mind that driving situations have a great importance in the first part of this work. Then, the last new contribution of this work resides in the multimodal approach with a *vibroacoustic space*. This space is presented in Chapter 8 and allows us to understand the perceptual dimensions of vibroacoustic stimuli of Diesel cars.

1.3 Axes of work

The Diesel engine is a very complex source and work on it appears, first, as a very vague issue. Here are the different steps led during this work in order to characterize the sound and vibrations, typical properties of Diesel vehicles.

1.3.1 When can we recognize Diesel features?

As we have precised in paragraph 1.2.1, two preliminary experiments have initiated the work in order to (i) reckon with the Diesel "reputation" in 2008 and to (ii) verify how different kinds of Diesel motorizations were perceived and especially, differentiated by people. However, the main issue is to *define what* the Diesel sound is. Who better than Diesel drivers could define this *when* Diesel vehicle is the most recognizable? The first question constitutes the first important point of this work. Before launching into explanation of perception of Diesel noise, we have to find some representative operating states which summarize Diesel features.

Therefore, a third experiment [43] has allowed us to find which driving situations best represent Diesel character[8]. With a listening experiment, people were able to identify two prototypical operating conditions (very often named *driving situations* in this document), characteristic of a Diesel sound. This step makes it

[8] Named Dieselness in this document too.

possible to concentrate the study on these situations, characteristic of what we call Dieselness.

The Dieselness issue has already been studied by different teams by focusing especially on the specific knock noise [16] [18] (named "impulsiveness" in some articles [17] [20]). Here, we take into account the global noise with an experimental perceptive test. By using the *Dieselness* term, we want to refer to Diesel character, which stimuli remind participants of their experience with a Diesel car. The axis of work chosen was to let people make up their own idea of Dieselness definition (Fastl [20] and Patsouras [19] [44] define this Dieselness term as *"the typical sound character of Diesel engine"*). However, in order to guide participants during the experiment, elements of definition about *Dieselness* term have been given to them such as *"up to what point does this stimulus corresponds to a typical driving situation of a Diesel car? In other words, up to what point does it recall a Diesel stimulus? Up to what point does it allow to be aware of a Diesel car?"*.

Finally, the thesis work presented here, limits oneself neither to a particular driving situation such as idle for instance - often referenced in scientific literature and the most used in automotive industry with 2^{nd} full load and 3^{rd} full load (cf paragraph 2.2.3 p 22 for an explanation of those two situations) - nor to a single geometry of engine (by keeping cars from different classifications).

1.3.2 Which *sound space* for typical driving situations of Diesel?

The characteristics of any sound source can be summarized with the following four notions: pitch, intensity, duration and timbre. The first three are understood by everyone without difficulty. Concerning timbre's definition, the scientific community is inclined to define it as, "all except intensity, pitch and duration". Indeed, according to American Standards Association (1960), the timbre's definition is valid as long as loudness, pitch and perceived duration of stimuli are kept constant. As we did not set those three parameters in our different experiments detailed in Chapters 6 and 8, we can not really speak about the timbral space even if our approach is similar.

After having defined typical Diesel driving situations, we are therefore interested in the corresponding *sound space* with a dissimilarity experiment. Even if sounds of different nature (steady and unsteady operating states) have already been studied for Diesel source, this step is a rather new approach.

1.3.3 What is the influence of vibrations on Dieselness perception?

Most studies focusing on interaction between sound and vibrations deal with two main topics: the influence of one on the other on the perceptual threshold and the interaction of both on a third parameter. This third parameter concerns very often the comfort issue [26] [27] [45] [46] [47] in the automotive domain. Indeed, sounds and vibrations are inevitably complementary in a vehicle's cabin. However, in literature, the Dieselness question has always been treated only with the sound component.

As some authors were interested in vibration's impact on sound perception thresholds, on loudness evaluation or on global comfort, we focus on the influence of this factor on Dieselness rating. However, as far as we have been able to take into account, it is difficult to compare the different studies whose main parameters fluctuate from one experiment to another (different test conditions, frequency range studied or choice of axes of vibration reproduction). But, the different studies agree that vibration's influence is very weak even nonexistent [26] [48] on annoyance (or discomfort issue).

Does this vibration component play a great role in the perception of Dieselness? Also, do French and German participants evaluate in the same way as without vibrations, the situations which best represent Dieselness? These are the issues which are addressed and dealt with in Chapter 7.

1.3.4 What is the influence of vibrations on Dieselness *sound space*?

We do not linger here to say that this last step allows to show the vibration's impact on the Diesel *sound space*. The innovation in this work is to build a multimodal space thanks to vibroacoustic stimuli. To our knowledge, no scientific study has already taken into account this type of stimuli.

This chapter has allowed us to introduce the automotive and scientific contexts before finishing with the four main problems of this study. After a first part devoted to a theoretical approach by introducing the "object" of our study, the Diesel engine through objective (Chapter 2) and subjective (Chapter 3) approaches, the second part will focus on experimental aspects with one chapter for each axis of work (Chapters 5, 6, 7 and 8).

PART I

THEORETICAL PART

Chapter 2

Diesel vehicle: a physical source

The internal combustion engine converts chemical energy contained in fuel into mechanical energy generated by the explosion. The resultant force applied on the cylinder piston, is transmitted to the crankshaft *via* the connecting piston rod. The vehicle propulsion has its origin in this mechanism that creates the coupled force.

This second chapter introduces the framework on which the thesis is based, namely the Diesel vehicle. It contains two parts: on the one hand, we focus on the mechanical functioning of Diesel engine (paragraph 2.1) and on the other hand, we focus on the noise generated by its mechanics (paragraph 2.2).

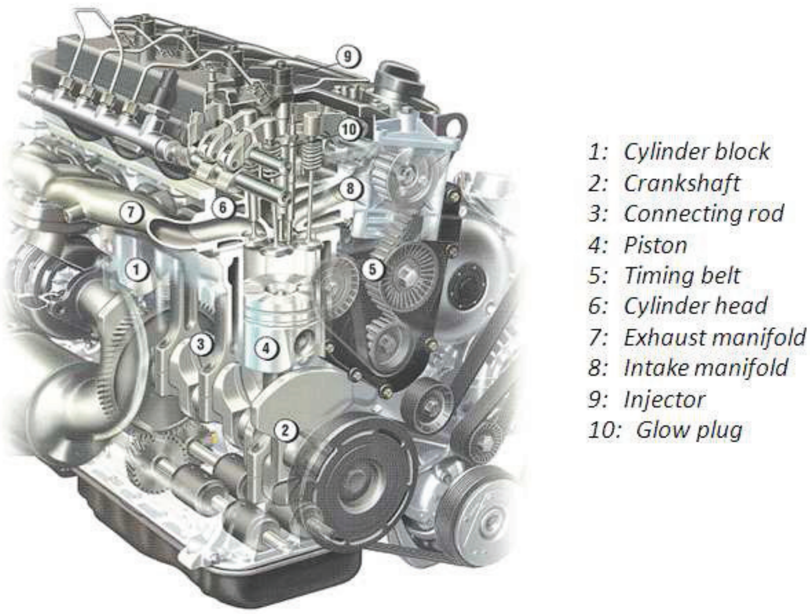


Figure 2.1: Global overview of a 4-cylinder Diesel engine with main mechanical parts around combustion chamber (Renault source: “L’auto en fiches”, R&D Communication, 2003).

2.1 Diesel mechanism

There are several types of automotive engines which differ by:

- the combustion model - by ignition with a candle spark (like for gasoline engines) or by self-ignition of gas (like for Diesel ones);
- the number and the geometry of the cylinders - the most common engines have three, four or six cylinders. They are organized in line, in "V" or flat. Engines with four cylinders in line represent the great majority of the French Diesel market;
- the number of motor time - two or four strokes.

2.1.1 Engine cycle

Let's focus on the cycle of a 4-stroke Diesel engine. Each cylinder of the engine runs in the same manner:

- 1^{st} stroke : **the intake**

The intake valves open up before the closing of exhaust ones. When the piston goes down (from High Death Point HDP to Low Death Point LDP), it causes a depression in the cylinder. Once the LDP is reached, the intake valves close up. In this case, the gas pressure is equal to the atmospheric pressure.

- 2^{nd} stroke : **the compression**

All valves are closed and the piston rises from the LDP to the HDP. The gas compression ratio becomes important, and the self-ignition of air/fuel is possible. The crankshaft ends its first round here.

- 3^{rd} stroke: **the explosion (combustion) and the firing stroke**

Just before the HDP, the fuel injected into the high pressure environment goes up in flames and the gases explode. Important values of pressure gradients are responsible for the characteristic Diesel sound. Due to the exhaust gas pressure, the piston goes down, transmitting through the connecting piston rod, a force to the crankshaft. Before the return of the piston to the LDP, the exhaust valves open up. This step constitutes the driving force.
Figure 2.2 p 15 shows the maximum pressure derivative which characterizes the sudden rise in pressure when the main combustion happens (paragraph 2.1.2).

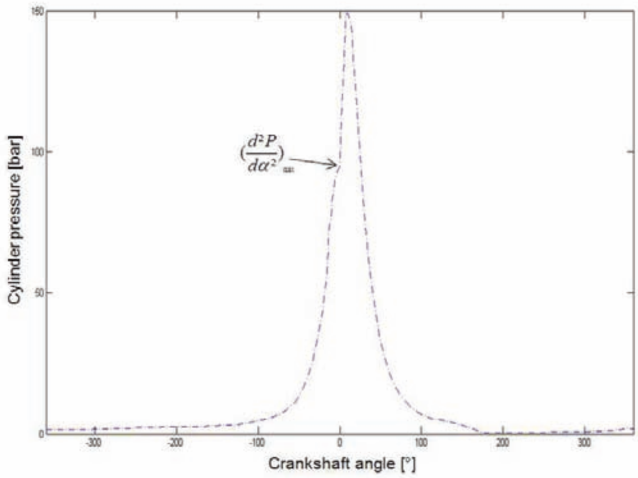


Figure 2.2: Example of cylinder pressure, responsible of the characteristic Diesel sound during combustion.

- 4^{th} stroke : **the exhaust**

The exhaust valves are opened and the piston rises again; the cylinder volume is reduced and the burned gases are ejected through the exhaust system. The crankshaft ends its second round and concludes the 4-stroke engine cycle.

Therefore, the Diesel engine works in a cyclic manner[1], with a cycle repetition every two rounds of the crankshaft. The steps described here for a single cylinder are valid for each cylinder that makes up the engine. Figure 2.3 p 16 presents the 4-stroke engine cycle.

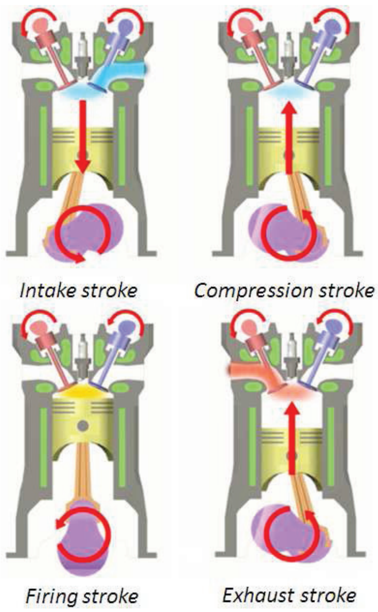


Figure 2.3: The 4-stroke engine cycle with intake, compression, firing (combustion) and exhaust strokes (http://cset.mnsu.edu/).

2.1.2 Combustion phenomenon

For Diesel engines, cylindrical pressure is more than two times higher than the one of the gasoline engine. Therefore, the force emitted from Diesel engine is stronger and it makes more noise, especially in some situations like starting up the motor in the morning or at idle.

During combustion, the explosion (paragraph 2.1.1) has a key role in the generation of engine noise. Indeed, characteristic Diesel noise called Diesel knock has its origin in this explosion. Two factors affect this Diesel knock: the combustion itself - which represents the primary excitation source linked to the explosion forces - and the impact between piston and cylinder liner (paragraph 2.1.3) - which corresponds to the secondary excitation source. In short, the characteristic Diesel knock is an amplitude modulation due to the vibroacoustic response of the structure [49]. The excitation forces of Diesel knock are due to the abrupt delayed combustion of the fuel which is left unburned. This phenomenon is influenced by factors such as combustion chamber wall temperature or aerodynamic turbulences. Most of those factors behave randomly and may cause different combustion at each cycle.

In an experimental study, Ishihama [50] has demonstrated the interest of controlling the chamber's temperature to reduce Diesel knock. He has designed a special engine cooling system maintaining control of the temperature around the combustion chamber. Thus, the ignition delay was minimized and he managed to delay the fuel injection. As a result, the intermittent vibrations were suppressed and Diesel knock was successfully improved.

In recent years, technologies have been developed to reduce the Diesel noise: turbocharger or common rail to modify the noise and "silent blocks" or balancer shafts to reduce vibrations (Figure 2.4 p 17 presents those four technologies). Indeed, with a turbocharger, the ignition delay is significantly reduced and at the same time, the combustion noise. Technology of common rail[2] makes fine electronic control possible over the fuel injection

[1] An animation of the 4-stroke engine cycle is presented at http://pierremarandet.pagesperso-orange.fr/.
[2] Le Magazine de la Recherche et du Développement, n° 39, 2006.

quantity and a better fuel atomisation thanks to a higher pressure. The term "common rail" refers to the fuel injectors which are supplied by a common fuel rail which is nothing more than a pressure accumulator where the fuel is stored at high pressure. It maintains the same pressure in all cylinders and reduces this characteristic noise of Diesel engines.

Other solutions can be used in order to reduce noise due to vibrations. In addition to the engine

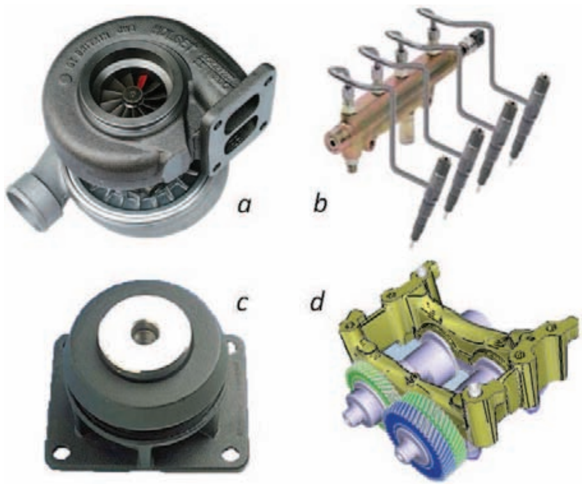


Figure 2.4: Turbocharger (a), common rail (b), engine mount "silent block" (c) and balancer shaft (d).

mount "silent blocks"[3] which dampen vibrations, or balancer shafts can be added to the engine. These are two cylinders that rotate twice as fast as the engine and that produce opposite vibrations. However, the price and the weight appear as negative points for this technology.

2.1.3 Impact piston/cylinder liner

In general, combustion chamber pressures mostly contribute to the overall noise of the engine. Secondly, the shock piston/cylinder liner, and thirdly, the mechanical impacts. Noise created by the impact between piston and cylinder liner has been studied with experimental approaches [51] or with a model [52].

In each cylinder piston motion is converted into rotating motion by the crankshaft. At HDP position a shock occurs between the piston head and the cylinder liner (Figure 2.5 p 17). This movement, in addition to the combustion, occur almost at the same time. Some studies indicate that this piston swing is dominant for turbo-charged engines [53]. Anderton and Duggal [54] even conclude that vibrations in 1500-3000 Hz frequency range are characteristic of the piston impact.

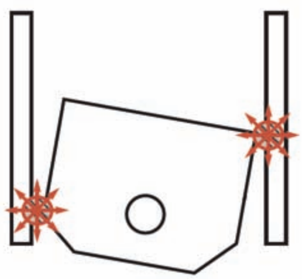


Figure 2.5: Impact between piston and cylinder liner during the piston swing.

During his PhD thesis, Flavignard [55] cites the study realized by Aouichi and Herrmann in 1989 [52]. They realized a piston motion model and concluded that this rigid block model was sufficient to rebuild the complete movement of it from few measurements. According to Flavignard, different parameters must be taken

[3] To avoid vibrations transmission to the body, the engine is hanged by buffers and is uncoupled from the engine compartment. Those attachment points are systematically integrated now.

into account in order to limit this noise shock. Indeed, the solutions used to reduce this noise impact are based on an optimization of parameters such as piston design, gravity center position or even advance of the ignition.

2.1.4 Injection

Fuel injection is one of the key factors of combustion. Also, two types of injectors can be distinguished: the *direct one* with the fuel directly injected into the cylinder (which is commonly integrated in engines nowadays) and the *indirect one* with the fuel injection made first, in a pre-chamber. Despite its benefits with a better combustion and a lower consumption, the *direct one* produces more noise. High injection pressures (from about 1000 to over 2000 bars) generate a mechanical impact on the structure. The fallout of injector needle causes additional noise too. Therefore, the main injection is preceded by a pre-injection. When the piston rises (just before reaching its HDP position), the pre-injection of small fuel particles allows to start the combustion. Therefore, it becomes less violent and less noisy[4]. Then, when the HDP is reached, there is a second injection. As there is less fuel quantity to burn, noises are reduced. With the hood closed, the injection noise is not very noticeable but this injection can represent a significant source of noise.

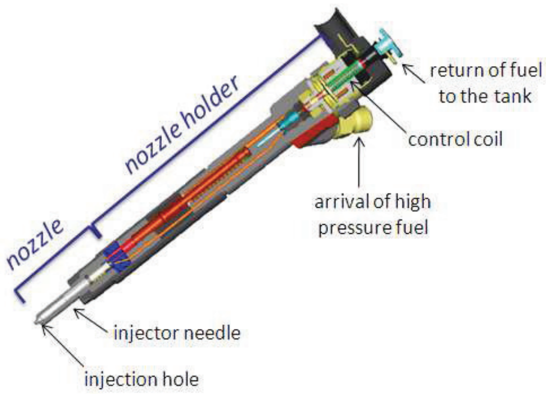


Figure 2.6: Global overview of an injector with its main mechanical parts.

Like the combustion noise, noise produced by the injection mechanism can be perceived as an annoyance. With important acoustical development works on all parts of the engine, a new technology of direct injection engine has been developed. The result was a reduction of 4 dB(A) of the injection noise. Technological solutions integrated for a better injection is: two pre-injections that limit the knock noise, then a main one, and finally two other post-injections that allow to burn residual soot[5].

2.1.5 Intake and exhaust

Intake and exhaust noises come from the air, the sucking and expelling when valves open and close. Intake noises come from the duct entrance that goes to the combustion chamber and can be optimized if mufflers are put in the circuit[6]. However, in their study, Ishii et al. [56] consider that cabin interior noise can be dominated by intake and exhaust noises to such an extent that they take into account only those two sources to design a new sound inside the cabin.
Figure 2.7 shows an example with the emergent harmonics for intake and exhaust noises of a 4-cylinder car.

2.1.6 Conclusion

In 2005, the future way for Diesel engines sound come down to two main points[7]:

- ensure a better mixing between fuel particles and swirl (rotational motion of the air when the piston goes down to the LDP). On one of the Renault flagship engines, this movement has been optimized by positioning the intake valves in opposition;

[4] Le Magazine de la Recherche et du Développement, $n°$ 36, 2005.
[5] Le Magazine de la Recherche et du Développement, $n°$ 38, 2005.
[6] Glossaire acoustique, Renault, 2005.
[7] Le Magazine de la Recherche et du Développement, $n°$ 36, 2005.

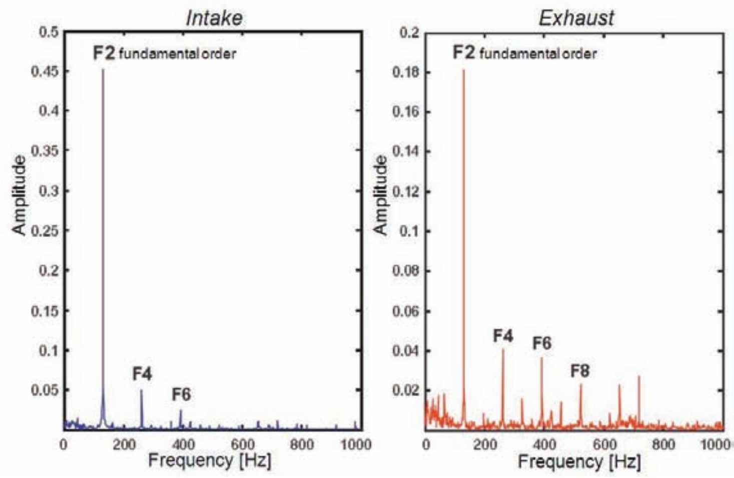


Figure 2.7: Spectra of intake and exhaust noises (4-cylinder engine at 4000 Round Per Minute) with their main even harmonics [1].

- and produce thinner fuel droplets.

To succeed in this quest of excellence, the Homogeneous Charge Compression Ignition (HCCI) system is born. This technology reduces the consumption by 15% while conforming to the European standards[8]. During combustion, the produced energy is released without flame front at low temperature. Moreover, all fuel in the combustion chamber is burned at the same time[9]. On an engine which integrates technologies as direct injection, pressure detection in cylinders or random climb of valves for instance, HCCI allows to approach the efficiency of the Diesel engine without using expensive systems of NOx[10] treatment. As it burns fuel at low temperatures, the heat energy lost during combustion process is reduced. Accordingly, it emits less carbon dioxide.

Even if we do not display all mechanical parts of the Diesel engine, this first part allows us to figure out the complexity of this kind of engine: both by the quantity of different pieces and by the noise that each one emits. We have focused on main mechanical components around combustion chamber which participate to the Diesel knock: piston head and cylinder liner, injector or intake and exhaust valves.

Therefore, in the second part of this chapter, we are going to present what spreads and contributes to the general noise (more than the simple components' functioning of vehicle).

2.2 Diesel engine: a complex source

Automotive noise is the result of a superposition of different noise sources. In this section, we refer to several parameters that contribute to the characteristic Diesel knock. Motor geometry (paragraph 2.2.2), transfer paths (paragraph 2.2.1), "use of the vehicle" (paragraph 2.2.3) and also vibrations (paragraph 2.2.4) are any non-negligible variables in the production of Diesel noise. Acoustic studies made on modern Diesel engines allow the identification of different sounds [57].

2.2.1 Two transfer paths (solid pass and airborne transfers)

Inside the cabin, the driver and other occupants perceive engine noise through two transfer paths:

[8] Euro emission standards set maximum limits for pollutant emissions of new vehicles. Euro I standard came into force in 1993, Euro II in 1996, Euro III in 2001 and Euro VI will be applied from 2014. According to Euro VI, the maximum NOx emissions should be reduced by 80% compared to the previous requirements of Euro V.

[9] Internal study of GM Europe in 2007.

[10] Compounds of nitrogen and oxygen which include nitric acid and nitrogen dioxide gases. They are produced mainly by burning fossil fuels.

- the solid pass - the vehicle's body spreads the vibrations which come from engine compartment. This transfer path is rather responsible for the frequencies transfer of around 20-300 Hz;
- the airborne - each source spreads alone and is transmitted to the cabin. This transfer path transmits the middle and high frequencies (500-1500 Hz).

Those two main transfer paths spread all sources generated by the functioning motor.

2.2.1.1 Solid pass transfer

Transmission of engine vibrations to the vehicle body is made by the solid pass way through filter rubber blocks. Those blocks support the engine and are designed to reduce the vibration's transmission to the cabin. Vibrations from the intake and exhaust tubes (paragraph 2.1.5) spread by this solid pass path too. While driving the vehicle, another sound contribution participates to the global noise of the car: the road noise. The wheel/road contact causes vibrations that spread to the structure through the tires.

For speeds less than 50 kph, the engine is the principal source of the noise produced in the cabin. Beyond this speed, road noise (vibratory phenomenon from 80 Hz to 2 kHz) then wind noise (1 to 5 kHz) contribute mainly to the global noise (paragraph 2.2.1.2). According to Kraemer [58], the road noise rises with the square of the vehicle speed.

2.2.1.2 Airborne transfer

Sources like intake and exhaust noises spread with this transfer path. At a high speed (generally higher than 80 kph), wind noise is more salient than road and engine noises. Wind noise comes from the air flow around the car and its level is linked to the turbulence noise. It can be spread by a direct way when the source is airborne or spread through ducts [58]. Its noise level rises with the cube of the vehicle speed.

2.2.1.3 Both transfers

It is difficult to reduce a single source to only one transfer path. Besides, Arz [59] remains that Diesel knock noise comes from both transfer paths. Engine vibrations are transmitted to the body by a solid pass path through interior panels like floor, roof, dashboard or even windows. The acoustics radiance is made by the airborne one. These different excitations contribute to the global Diesel sound.

Several articles have been devoted to the identification [60] and to the hierarchy organization of vibrations transfer paths [61] [62]. Those different studies agree with the fact that the vertical direction (piston head, connecting piston rod and crankshaft) plays the key role in the transmission of the combustion noise. Kojima [61] is even more precise and concludes that:

- the vertical direction is predominant on the frequency domain above 1.6 kHz and that its contribution, alone, represents between 50% and 90% of the combustion noise;
- the superior direction (piston head and cylinder liner) plays a key role in 315-630 Hz band and that at 500 Hz, represents more than 90% on the combustion noise contribution.

It clearly appears that the optimization of the transfer paths is a strategic axis in order to reduce combustion noise.

2.2.2 Engine geometry

As precised in the first part (2.1.1), the same mechanism occurs in each cylinder of the engine, whatever their number and their geometry. However, each cylinder has its own cycle, with an offset between them. So, their explosions are slightly different. These events are estimated with crankshaft angle ($\phi = \frac{2\pi}{n}$ for engines in line - with n, number of cylinders), where a cycle of engine corresponds to 720°, *i.e.* two crankshaft rounds. The most common configuration of the ignition order for a 4-cylinder Diesel engine is 1^{st} cylinder - 3^{rd} cylinder - 4^{th} cylinder and 2^{nd} cylinder. Figure 2.8 shows two kinds of engine geometries with four cylinders in line and six cylinders in "V".

Due to the periodic phenomena of a 4-stroke engine, the engine noise is composed of an harmonic structure. Functioning of this kind of engine gives a frequency of events' apparition of all two crankshaft rounds for one

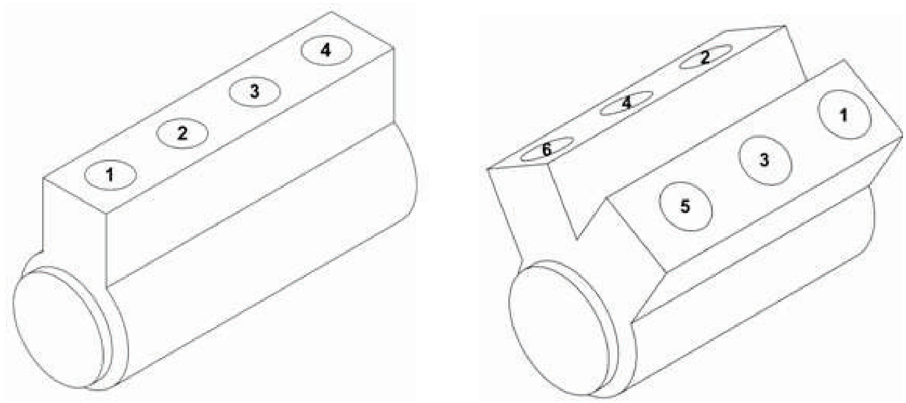


Figure 2.8: Examples of two engine geometries: four cylinders in line (left) and six cylinders in “V” (right).

cylinder. Fundamental frequency of its noise spectrum is half of the frequency of crankshaft rotation. We can define a frequency of fundamental repetition f for each event:

$$f = \frac{1}{2}\frac{k}{60} \tag{2.1}$$

with k, the engine revolution speed [RPM[11]],
and f, the main frequency of one cylinder [Hz].

The phenomena appear n times per engine cycle. Therefore, the fundamental harmonic h_f, for those particular events becomes:

$$h_f = \frac{n}{2}\frac{k}{60} \tag{2.2}$$

with n, the number of phenomena per cycle.

For a multiple cylinders engine (that we consider identical), the apparition frequency of each phenomenon is now multiplied by the number of cylinders:

$$h_n^m = m * \frac{n}{2}\frac{k}{60} \tag{2.3}$$

with m, being the number of cylinders of the engine.

The principal frequency f for an engine revolution speed k of 3000 RPM is equal to 25 Hz. Fundamental frequency h_f in the same engine revolution speed depends on the cylinders' number. It will be of 100 Hz for a 4-cylinder engine and 150 Hz for a 6-cylinder one. The number of cylinders (equation 2.3) has an impact on the emergent frequencies named engine orders or engine harmonics. For a 4-cylinder engine, the perfect spectrum is made up even harmonics. In reality the eigenmode of the engine and of the vehicle body, combustion dispersions from one cylinder to another one, dispersion phenomena cycle-to-cycle, evolves of the engine revolution speed or transfer paths, disturb the theoretical periodic system. Some fractionnal residual components with less or more stronger appear. However, the 4-cylinder engine sound keeps a part of its validity: the presence of main even harmonics is the typical signature of this type of engine.

Despite a better handle for specific engine architecture and of parameters' adjustements - combustion chamber geometry, compression ratio, quantity of injected fuel, impact piston/cylinder liner (paragraph 2.1.3) or injection type (paragraph 2.1.4) - engines still cause random phenomena when explosion of gas happens. Moreover, these phenomena give different kinds of noise during combustion. As cylinders do not have the same combustion law, explosions of a same cylinder, vary from one cycle to another one. The main frequencies correspond to the apparition of energetic phenomena which spread in the structure. There are combustions, inertia forces, shocks, intakes and exhausts, without forget accessories and gear box.

[11] Round Per Minute.

In order to conclude, the perceived character of Diesel knock is composed of three different features [16]:

- the basic impulsiveness defined by the repetition frequency which is the second order for a 4-cylinder engine (30 Hz at idle of 900 RPM for instance);
- cylinder-to-cylinder variations with differences in the firing process between the cylinders result in additional rhythms. These rhythms follow the 0.5^{th} and 1^{st} engine order (7.5 Hz and 15 Hz for idle at 900 RPM);
- shot-to-shot differences with variations of the firing of a cylinder over time.

Moreover, some studies which compare acoustics of 3-cylinder and 4-cylinder cars conclude that their engine sound are different and that the noise interval is more important during driving situations like acceleration [63].

2.2.3 Use of vehicle

By using the expression "use of vehicle", I want to refer to driving situations that all drivers can experiment when they are driving. Indeed, according to their driving manner (undershoot or overshoot) but especially, the situation in which they are driving, the engine does not answer in the same way. Therefore, it does not produce the same sound. The main parameter which has a key role about the engine sound, is the pedal load. Indeed, in accordance with this parameter, the injector pression and quantity of fuel in the combustion chamber will not be the same. The stronger the pedal load, the more quantity of fuel there is. So, the more noise is created because more fuel has to be burned. For instance, at idle, without charge on the acceleration pedal, the quantity of fuel injected is the sufficient quantity to maintain the lowest engine speed. For steady situations like *50-kph* or *130-kph*, the quantity corresponds to the pedal load on which the driver places (less for *50-kph* and more for *130-kph* for instance). Concerning *deceleration*, as the typical noise of engine is not present (without injection), the only forces are the inertia ones. Finally, during *acceleration*, the engine is very excited and a bigger quantity of fuel is injected, more than in other examples mentioned before.

Therefore, different kinds of driving situations can be used by people during a daily-life trip: in city center (*hot idle*, *50-kph*, *traffic light start* or *traffic jam* for instance), on road (*90-kph* or *110-kph*) and on highway (*130-kph* and *acceleration* [64]). However, automotive industries used to work with particular unsteady situations named 2^{nd} full load or 3^{rd} full load. The first one corresponds to the situation when we start at 1000 RPM in 2^{nd} gear, then we press the acceleration pedal and drive at top speed. It is the same for the second one, but by starting recordings in 3^{rd} gear. Indeed, they are easily repeatable and they allow to have a broad spectrum in order to have a global view of all noises generated by the functioning of the engine (paragraph 2.2).

Most sudies on the Diesel vehicle have focused on one particular driving situation: the idle[12] [26] [27] [44] [65]. Moreover, Bodden and Heinrichs [16] precise that the perceptually most critical situation for Diesel impulsiveness is usually idle. Most engines run into a strong and clear impulsiveness in this situation and the other masking sounds are rather weak. They also add that in this situation, the interaction between the vehicle and the driver does not exist, which certainly plays a main role in Diesel perception. The knocking can not be interpreted as a feedback, and, furthermore, the attention of the driver is not blocked by driving the car. This remark highlights the question of the context influence in Diesel noise perception (paragraph 3.2.2.6 of Chapter 3).

But other authors have worked on other driving situations of Diesel vehicles like Heinrichs and Groemping [66] with a comparison between idle, constant speed, traffic light start and 2^{nd} gear full load. If sound quality should be evaluated with regard to customer relevance, a field test is, in general, necessary. Driving situations studied in the various experiments are as stationary as unstationary. The first ones are easier to realize and reproduce. For the second ones, the difficulty, especially during the recording of sound tracks (Chapter 4), is to control the pedal load. At Renault, the "brilliant sound" works [67] to identify two broad driving situations that contribute to the "brilliant sound"[13]: the 2^{nd} full load acceleration and the acceleration from 0% load to 100% load.

[12] In general, authors do not precise if they refer to hot or cold idle. However, during this PhD work, I have worked on *hot idle*. This term is used in contrast with *cold idle*. Indeed, *cold idle* refers to idle just after starting up the motor. *A contrario*, *hot idle* refers to idle when you are stopping to a red traffic light for example whereas you have started up the motor a long time ago and that engine is warm. In the following, I will always use *hot idle* term to speak about my experiments.

[13] We call "brilliant", the performance sensation, with fluency impression, nervousness, swiftness and lightness.

2.2.4 Vibrations

The vibroacoustic behavior of the vehicles is due to the strong coupling between the powertrain, the body and its seats, the facing door or the front and rear axles. These subsystems are linked by connecting parts as the engine mount (already mentioned in paragraph 2.1.2) which has two main functions: (i) to ensure the static link between the subsystems and (ii) to limit the transmission of vibrations between them. Two types of suspensions are commonly used. The "all-rubber" whose function is to only filter, and the "hydro-elastic" suspension whose rubber part filter the vibrations and whose hydraulic system allows to absorb the low frequencies ($f < 25$ Hz). The two main structure-borne excitations are:

- the powertrain: between 0 and 25 Hz, the road's roughness solicits the natural modes of the engine at engine mounts level. Beyond 25 Hz, its main sources are the explosions in cylinders. Between 25 and 200 Hz, one speaks about booming noise and between 200 and 800 Hz, about rumbling noise;
- the tire/road *via* the front and rear axles through the road. Automotive industries rely heavily on modeling to characterize and improve this vibrational behavior.

The powertrain is the main source of vibrations in the cabin. Indeed, the main vibrations come from motions of rotation and translation of different parts of the engine. During its functioning, the crankshaft rotates around its main axis and moves the center of gravity of the engine. The forces and torques, responsible of vibrations, are so created. Also, with the continuous up-and-down movement of the piston in the cylinder, some efforts are also generated. However, the crankshaft and the piston represent only two examples of mechanical parts which cause vibrations felt in the cabin.

Figure 2.9 presents the level of vibrational excitation as a function of engine speed and frequency upstream from the engine mount (at the top) and at a motor mount (at the bottom). In the upper part of

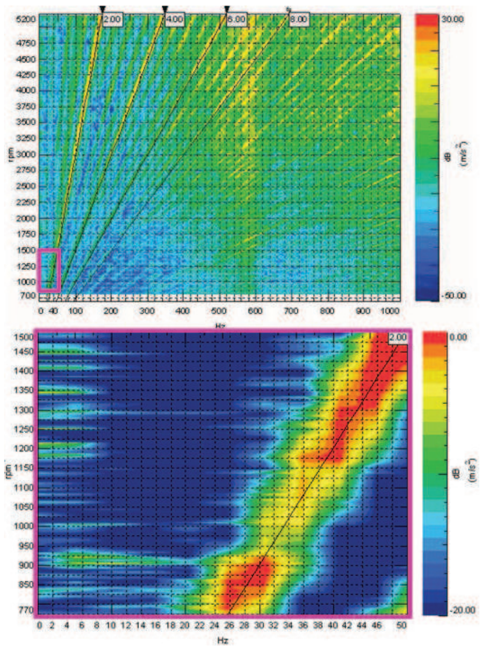


Figure 2.9: Example of a vibrations spectrogram of powertrain upstream from the engine mount (top) and at a motor mount (bottom) [2].

Figure 2.9, it is clear that even harmonics are dominant upstream from the engine mount with the first engine harmonic H_2. In the bottom part, the vibrations spectrogram is measured at the motor mount. The frequency range of the measure is precised across the pink square on first chart. We can see that H_2 is the dominant component and this is this one which will be mainly transmitted to the cabin.

The vibrations at idle are principally felt through the floor, the seats and the steering wheel. Through an internal study conducted by Renault in 2008 [68], which focused on the analysis of floor and steering wheel's vibrations for 4-cylinder cars at idle, the engineers show the presence of two vibratory phenomena in frequency ranges 23-25 and 27-28 Hz. Moreover, the maxima are located for x and z directions (for both floor and steering wheel). Also, the two measure points on the floor show an asymmetry of the floor's response along z axis. This study confirms that the frequency range 20-30 Hz presents body modes as well as modes of front and rear axles. The observations on the vibratory phenomena for the floor between 20 and 29 Hz are also present for the steering wheel but closest to 30 and 35 Hz.

These vibrations are obviously harmful to the user but also for the car itself. A material submitted to vibrations destroys itself quickly and its lifespan is reduced. In order to improve this, several solutions are considered: this is called the balancing. At each engine cycle (two revolutions for a 4-stroke engine and only one for a 2-stroke) on the same steady engine speed, all components reproduce the same movement, the same forces and the same vibrations. But within the same cycle the vibration amplitude varies as for combustion phenomenon which is not so cyclic (paragraph 2.1.2). As for the sound, engineers therefore seek to reduce or eliminate the most harmful vibration of order 1. To balance this force (or the torque), it is sufficient to oppose a force (or torque) of the same intensity and opposite direction: this can be achieved through the balancer shaft (paragraph 2.1.2).

2.3 In the future?

With the hardening of European standards on polluting emissions, technical solutions must be found to "stay in the race". However, important parameters shall be considered in order to take up this challenge. Therefore, the automotive industries are now undergoing profound technical changes to achieve ecological demands. The new standards for polluting emissions reduction urge them to favor CO_2 in the compromise between consumption, CO_2, performance and comfort. Car manufacturers are working on different technologies: 3-cylinder engines, electrical or hybrid cars are the most popular. However, modifications of engines will induce potential changes in noise and vibration and will no longer conform to European regulations.

We present here two technologies which will participate soon to the upheaval of the urban sound environment: the downsizing and electric vehicles.

2.3.1 Internal Combustion Engine (ICE) vehicles and downsizing

A small difference in principle functioning of the engine allows to distinguish easily a Diesel sound (with knock noise) to a gasoline one (without knock noise). Indeed, in gasoline engine, the air and the petrol are first mixed before their introduction into the cylinder. When the piston goes up a candle starts the combustion process. This combustion type, light in one point, creates some progressive energy emissions. Therefore, the produced noise by this process is less critical compared to the Diesel one. Beyond this mechanical difference, other criteria still divide those motorizations today. According to a study in 2001 (Etude Perception / Attentes Diesel in Renault), consumption - and price too - is the most important criterion between pro-gasoline and pro-Diesel when people purchase a car. Diesel users seem to be more attentive to the reliability and to the performances. Conversely, the gasoline motorization benefits from a stronger emotional context. Moreover, this study shows that gasoline cars refer to driving pleasure, are choosen for their nervousness and produce "relative silence".

The power of these motorizations has considerably increased for ten years thanks to new technologies: injection, valves, maximum engine speed and turbocharger for gasoline engines and injection, turbocharger, Exhaust Gas Recirculation (EGR) or combustion chamber for Diesel ones. However, the "needs" of customers in terms of power have not increased as fast as engine potential (which follows the "sporty" tendency)[14]. Therefore, downsizing the engine is an opportunity to reduce CO_2 emission while maintaining the power required by customers. This process reduces the engine size and, the cylinders' number too, while keeping the same power. Besides, an internal study at Renault has compared the vibroacoustic perception of two Opel Corsa: a 3-cylinder and a 4-cylinder car [69]. Although objective measures of sound and vibrations give people an unfavourable opinion of a 3-cylinder car, the subjective sound perception is on the other hand positive. Concerning the vibration component, it does not distinguish between both cars. Only 10% of polled persons judges the 3-cylinder car as noisy and only 5% are complaining about vibrations. For instance, Yoshinaga and Namikawa [70] have worked on this type of vehicle and concluded that a 3-cylinder car without balancer shaft but with HCCI technology generates high level of vibrations and noise. Moreover, different analyses of

[14] Internal presentation of Group Performance/Consommation in 2007: "Downsizing" : Pourquoi et comment ?

automotive press about VW Polo 1.4L, VW Polo 1.2L, Hyundaï Matrix 1.5L and Opel Corsa 1.0L [71] conclude negatively and positively points out this kind of motorization with respect to roughness at high sound levels which is annoying and vibrations at idle. Concerning positive features, verbalizations cited by people come down to brilliance, musicality, pleasure and silence. One article mentions the deaf character of noise, but all notice the particular sound of 3-cylinder vehicles (without precising if it is in negative or positive terms).

2.3.2 Electric vehicle

The petrol resources which have become scarce or the fight against the environmental pollution (noise or air) participate also to the development of the new transport means, an electric vehicle.

Since the beginning of 90s', various studies agree to conclude that one of principal acoustic sources of electric car's noise is the wind noise [72]. Indeed, in one of their studies, Otto et al. [73] concluded that the electric car has wind noise and wind noise loudness levels, equal to that of gasoline vehicles. However, at low speeds (50/60 kph), the gasoline car is judged less windy than the electric one. Of course, there are other kinds of noises like engine or powertrain noises which add to mask wind noise in the case of gasoline vehicle. Also, the tire/road noise seems to be important when the electric car is functioning. Therefore, electric cars lead to a different noise/vibration balance than ICE cars. Indeed, thanks to a tool developed with Genesis[15] based on partial loudness model which allows to identify the main perceived sound source with an ERB band representation, Lenindre and Guyader [74] show the contribution of each sound (of engine, of road and of wind) for Diesel, gasoline and electric cars. The "absence" of engine noise, the most important presence of road noise or the emergence of noises as squeak and rattle could characterize the future sound of electric vehicles and could be a disservice for this motorization.

As we have already precised before, the noise environment will be totally different and certainly a bit puzzling for people. Besides, Yoshinaga and Namikawa [70] precise that *"the Japanese Government announced in 2008 a goal of increasing the number of next-generation vehicles to at least out of every two newly sold automobiles by 2020"*. Not only the electric car interior noise can become annoying for users but also, the "exterior noise" seems to be dangerous for pedestrians and cyclists[16] [75] (because with less exterior noise at low speed). For this reason some actions have been taken by the US and Japanese governments with the expected outcome that "minimum noise" of vehicles shall be measured and legalized with standard methods and limited values [70]. In 2008, Nyeste and Wogalter [76] reproduced the same experiment realized in 2001 by Wogalter et al. [77]: they examined which sound could be added to quiet vehicles in order to provide cues for pedestrians and cyclists. Noises, from the most acceptable to the least acceptable, are ranked as followed: engine, white noise, hum, whistle, horn and siren. The same order was obtained regarding the preference question. So, we can see that people bring some importance into the engine noise. Despite substantial differences in method, results of those two experiments show high correspondences. Also, an inquiry made by INRETS[17] in France has shown that one third of French population is annoyed by vehicle noise [78]. So, electric vehicles provide a great opportunity for improving the daily life of city inhabitants. Electrification of cars will, thus, be an efficient way of reducing noise level in cities. But the hazard that electrical vehicles represent, some cars manufacturers want to equip their vehicles with particular sound. This solution would ruin one of the main advantages of electric cars as mentioned above. There is a clear need to develop a solution to find a compromise between the need for a less noisy environment in cities and a high level of safety for pedestrians.

2.4 Conclusion

After a first section in which we have focused on the main mechanical parts interesting to this study context, the second part has allowed us to understand how different kind of noises can be generated. Not only, the simple functioning of the vehicle produces the main noise and vibrations felt in the cabin (through solid pass and airborne transfers or engine mounts [46] notably), but also, noise and vibrations can be different according to the engine geometry and the user. Therefore, more than the complexity of the vehicle mechanics, this is, also, the use that people make. This contributes to the general noise.

[15] http://www.genesis-acoustics.com/.

[16] Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles in National Highway Traffic Safety Administration, 2009 at www.nhtsa.gov.

[17] National Institute for Research on Transportation and Security.

Key points of this chapter concerns the complex nature of Diesel engine noise, a mixture of different acoustic signatures. Mechanic process of Diesel engine and main excitation mechanisms, which produce its characteristic noise (and vibrations), have been presented. Compared to other motorizations like electric ones, we have noticed that Diesel does not only have defects anymore. Should we get to see a new type of noisyless engine in order to forget the bad image that sticks to the skin and accept the fact that a Diesel car is not only loud? In 2005, le Magazine de la Recherche et du Développement concluded that "the future of ICE tandem depends on some subtle compromises, but gasoline and Diesel should have their place in future cars".

The number of scientific studies in order to understand Diesel noise perception is subsequent. Combustion noise, considered as the main drawback of these engines, is largely treated. This defect, now better controlled, is regularly presented in different international conferences related to the field and is greeted by the press [79].

Chapter 3

Diesel vehicle: a perceptive source

Based on a physical approach, sounds produced by the vehicle's functioning are very different: periodic ones (*e.g.* functioning of a 4 cylinder engine) or random ones (*e.g.* squeak and rattle inside the passenger compartment). Based on a perceptive approach, the individual interpretation reinforces the complex features of the Diesel noise. It can be perceived:

- as sound pollution which contributes to the annoyance that people would want to see disappear. Car manufacturers pay particular attention to this kind of noise in order to reduce or even to eliminate them;
- as feedback to the vehicle's use. This feedback can be of two sorts: an explicit message and an implicit one. First, some people say *driving by ear*. Therefore, the engine noise, *e.g.* when one accelerates, indicates the good moment for changing the gear. Secondly, between *"my car makes some noise"* and *"there is noise in my car"*, we can distinguish two types of noises: normal and abnormal ones;
- as a bearer of sound quality. Indeed, in this case, the sound brings a message, decided and worked out by the automotive industries. This quality can be the result of sound design (Saint-Loubry [15] with her work on gasoline cars and Guyader [80] or Bézat [81] [82] on doors' closing noise).

For several years, car manufacturers have significantly reduced the noise levels of Diesel engines. This success has brought a new challenge: improve the Diesel engines' sound quality in cars towards a higher user appreciation. This has become a major challenge for car industries.

This PhD work is placed in a perceptual framework that takes into account subjectivity and individual specificity. The context in which the participant is put, *i.e.* his culture, his personality, his background or his motivation, is an important exterior parameter that modifies his reaction to a stimulus. Will a user when questioned about his or her Diesel sound (of his or her own car) answer in the same manner according to his/her age, his/her driving pleasure or his/her experience with the automobile?

This third chapter presents a subjective approach to the Diesel car. For the first time we focus on perceptual mechanisms of sound and vibrations. Moreover, we take into account a cultural approach since this PhD study deals with an intercultural context (paragraph 3.1). Secondly, we are interested in the sound quality domain which has spread in automotive industries for several years. We will tackle its main techniques (psychoacoustics indicators and methodologies) which contribute to characterizing the studied object (paragraph 3.2).

3.1 Perception

The term *"Perception"* is an active phenomenon. It can be achieved by two approaches. The *indirect* approach, supported by Neisser [83], explains perception like a succession of stages as *information treatment* in which the listener extracts the relevant information. *A contrario*, the *direct* one, named *ecological* (Gibson in 1979 [84] and Gaver in 1993 [85] [86]), sustains that world perception is direct, immediate, and does not need any intermediate representations.

3.1.1 Definitions

"Perception" groups together several ideas, tendencies or several domains. Indeed, it is linked to our five senses: seeing, tasting, touching, smelling and of course, hearing. But in the auditory domain, what is it "to perceive"? Is it "to hear" or "to listen"? Schaeffer [87] gives a definition of those two terms: *"listening is listen to hear and hearing is to be stricken by sounds"*. Specifically, listening to a car is to be able to evaluate its distance and even recognize its brand. This listening process is primarily utilitarian ("can I cross the street now?"), but it is really hard to describe the source. Hearing is to focus on the sound subject and its own specific features. This last approach also fits within the framework of another one - appreciation of the object.

3.1.1.1 Perception

Perception is defined as the reaction of people to an exterior stimulus which allows one to understand the world [88] [89]. Tardieu [90] reminds us that the perceptive activity can be described with two processes which do not take into account the same cognitive mechanisms: a "bottom-up" process, guided by the stimuli and their physical contents, and a "top-down" one, guided by the knowledge of the stimuli. Therefore, perception is based on both our capacity to collect environmental information and knowledge of the exterior world [91]. However, this simple definition does not have to mask complex mechanisms of perception nor reduce it to automatic processes associating one perceptive parameter to one physical phenomenon. Studying perception sums up to wondering how to use environmental information in order to build our representations.

In the daily-life context most sounds are bearers of messages. For instance, thanks to the sound emitted by a car, a pedestrian who is crossing the street knows when the vehicle is arriving - problem highlighted today with the silence of the electric car (Chapter 2). Perception appears to be the fundamental domain of this thesis.

3.1.1.2 Psychoacoustics

Psychoacoustics is the study of human auditory sensations. This discipline is at the border between Acoustics, Physiology and Psychology. Acoustics studies the nature and properties of sound waves arriving at the eardrum whereas Psychoacoustics is interested in knowing how stimuli are collected by the auditory system and how they are interpreted by the brain. It explains sound sensation provided by a sound by linking its physical parameters (as its intensity or its frequency) with perceptual ones (as its loudness or its pitch). In fact, two sounds with the same physical intensity are inevitably not perceived by people in the same manner.

This domain has especially allowed progress in the knowledge of ear functionality and its modeling. Moreover, it has emphasized four[1] main characteristics of the hearing sensation:

- the perceived intensity (or loudness linked to the sound pressure level, cf 3.1.2.2),
- the perceived pitch (linked to the frequency, cf 3.1.2.3),
- the duration (cf 3.1.2.4),
- and the timbre (linked to the spectral composition cf 3.1.2.5).

As already precised, perception allows the identification of objects, the recognition of their functioning state or even the identification of the cause of the poor functioning. Indeed, only with their ears some specialists can recognize the qualities of a motorization like a stringed-instrument maker does with his or her instruments. The notions of quality, aesthetic or pleasure are not only intrinsic to the objects but also, linked to the human, whichever sensory modalities are concerned.

[1] In 1751, in its Encyclopedia, Diderot evokes only three features of sound: *"the elevation degree between low and high pitch, the one of vehemence between low and loud and the timbre which corresponds to the comparison between muffled and brilliant"*.

3.1.1.3 Sensory analysis

Historically, the first purpose of this discipline was to determine the food sensory properties and to determine customers' preferences. In the automotive field, the brand can play an important role in the perception process [92]. Therefore, for several years sensory analysis has become essential for the automotive industry which puts the customer at the center of their innovations.

Also, before any perceptive experiments it is important to know which approach to adopt in order to better understand what the people like or dislike. Those two aspects group together several methods to measure sensory perception from our five senses. As part of this thesis work, I could rely on some testing methodologies from this discipline and I could adjust them to study Diesel engines (paragraph 3.2.2).

3.1.2 Sound perception

Let's be reminded here that the word "sound" refers both to the hearing sensation and to the physical phenomenon that produces it. By the perceptive aspect each person feels the sound and qualifies it depending on his sensitivity or his background, whereas by its physical aspect the sound is based on the propagation of a travelling wave and so on vibratory phenomena. In order to understand sound perception, let's focus on the ear's functioning.

3.1.2.1 The auditory system

The auditory system consists of the outer, middle and inner ears. The first two parts "transmit" the propagated wave while the third one "receives" it. An illustration of the ear's anatomy is done in Figure 3.1 p 30.

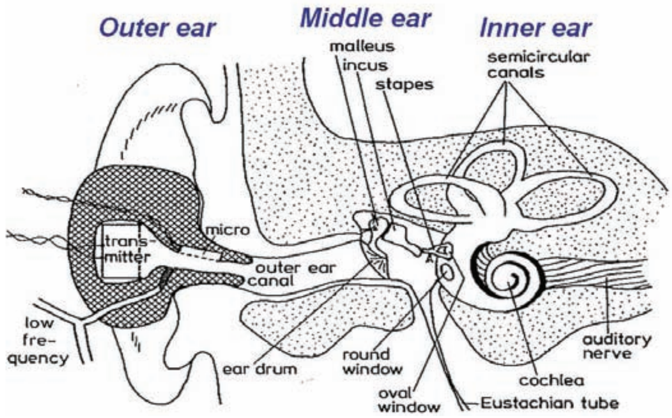


Figure 3.1: Ear anatomy with outer, middle and inner sections.

The outer ear

The outer ear consists of the pinna and the external ear canal which leads to the eardrum. The ear canal guides the acoustic wave to the eardrum. The shape of this canal creates a resonance phenomenon for frequencies between 1.5 and 7 kHz. The entire outer ear has the effect of increasing the sound intensity at the eardrum by a few dB in this frequency range.

The middle ear

The middle ear takes over for the wave transmission while protecting organs against possible destruction. It extends from the eardrum to the oval window (or vestibule window) and the round window (or cochlea window). It includes the eardrum and the ossicles (hammer, anvil and stirrup) and communicates with the back of the mouth by the Eustachian tube and with the inner ear through the both windows. Sound waves arriving in the ear make the eardrum vibrate which transfers the energy to ossicles. Those transmit vibration movements from the eardrum to the oval window, which in turn stimulates the liquid of the inner ear. This ossicles chain amplifies sounds of around 20-30 dB between 1 kHz and 10 kHz with a maximum at 4 kHz (as in the outer ear). The muscles of the eardrum and the stirrup can reduce excessively high amplitudes and can achieve optimum impedance if amplitudes are too low.

The inner ear

Its function is to convert mechanical energy into electrical waves, with the least possible information loss. It is made up of a labyrinth with the semicircular canals and the cochlea (a spiral bony cavity consisting of the membranous cochlear which houses the organs of Corti, the hearing receptors).

The amplification that occurs during the impedance adaptation between the different parts of the ear, is better for the midrange frequencies than for low and high ones. This feature is largely responsible for the main phenomenon of auditory perception: the audibility threshold, higher at low and high frequencies than at midrange ones. The transmitted wave encoded to the middle ear as nerve impulses is realized in two ways: both in frequency and in time [91]. These two encoding manners govern the sensitivity of the ear. Indeed, it is the basilar membrane of the inner ear which handles this encoding. The frequency encoding is ensured through a *tonotopic organization*. Because of the membrane rigidity which decreases with distance, the membrane base is activated by high frequencies while lower frequencies activate its end (named apex). Figure 3.2 illustrates this tonotopic organization. *Time* encoding is due to the membrane's movement which is at the beginning of

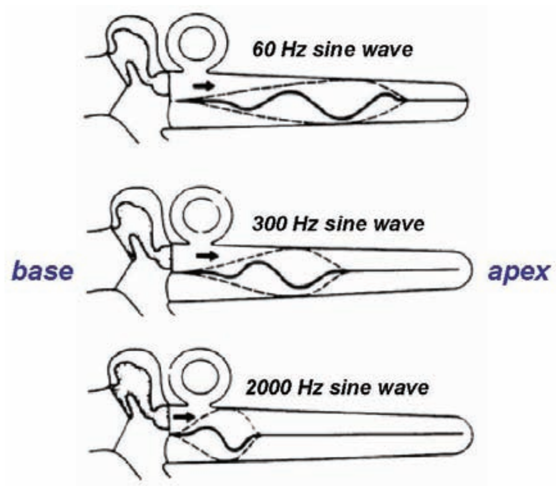


Figure 3.2: Tonotopic organization of the basilar membrane. For a low frequency sound (60 Hz at the top), wave peaks are near the apex of the cochlea whereas for a high frequency sound (2000 Hz at the bottom), peaks are near the base.

nerve impulses.

Let's describe now each of the four main criteria of auditory sensation, as listed above (paragraph 3.1.1.2).

3.1.2.2 Perceived intensity

In general when one describes a sound, the first evoked feature is its physical level. Indeed, in the case of an automotive context it is this parameter, governed by standards Euro V, Euro VI (cf footnote $n°$ 8 p 18) and the following (based on the exterior noise level), which validates the vehicle outing on the market.

Indeed, criteria have been chosen to "translate" the perceived intensity level because the ear's sensitivity is not constrained to the audible frequency range. According to Fletcher and Munson in 1933 [3], the perceived level is proportional to the logarithm of the physical level. If we take as reference a 1000 Hz pure tone at 20 dB, one can ask to a listener to adjust the level of another tone till the listener perceives the same level for both sounds. Therefore, we attribute to any sound perceived at this level, a loudness of 20 phon (cf paragraph 3.2.1 for the definition of phones). By reproducing this process for several levels of a reference sound we obtain the equal loudness curves (Figure 3.3).
These curves define the levels as function of frequency for which the intensity sensation of pure tones, in binaural hearing, is constant. They have been used to define the weighting curves, which allow to correct a level in dB,

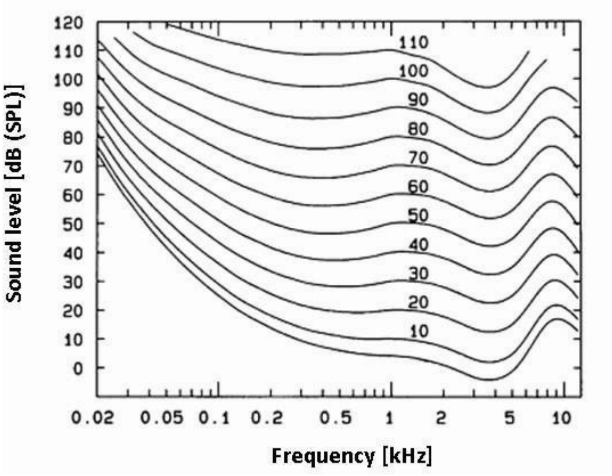


Figure 3.3: Equal loudness curves (according to Fletcher and Munson [3]).

in order to make it closer to perception. Three weighting curves are known and are more or less used:

- dB(A) based on the 40 dB loudness curve and which takes into account variations of the ear's sensitivity,
- dB(B) based on the 70 dB loudness curve,
- and dB(C) based on the 90 dB loudness curve.

Moreover, a phenomenon linked to the sensitivity of auditory system seems to be important: the *masking effect*. Although equal loudness curves allow us to have a good idea of the perceived level as a function of frequency and pressure level of pure tones, they do not take into account this effect. Indeed, the achievement of these curves has been done with non-simultaneously pure tones. However, the masking effect can be quantified by measuring the audibility threshold of a sound with another one that plays the role of masking sound. Figure 3.4 presents an example of this *masking effect*. It presents the increase in hearing threshold for different

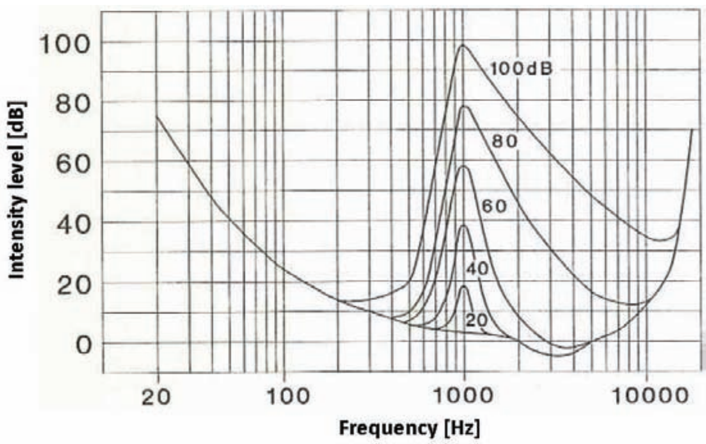


Figure 3.4: Masking effect: those curves show the increase of absolute thresholds with a masking sound (Bagot [4]).

frequencies and for different levels of masking noise. The curves show the elevation of absolute thresholds with a masking tone at 1000 Hz and for variable intensities (indicated over the curves). For the masking sound of 80 dB the absolute threshold for a sound at 800 Hz is of 50 dB, and the one for 3000 Hz is 30 dB. Moreover, as we have seen with the auditory system's description, the encoding of the sound signal is complex. It is based on filters' set which depends on the critical bandwidth. The high frequency waves excite only localized areas at the cochlea base (basilar membrane base) while low frequencies detected at the apex excite all parts and, therefore, high frequencies too (paragraph 3.1.2).

3.1.2.3 Perceived pitch

Pitch[2] is the sensory quality which allows us to say whether a sound is low-pitched or high-pitched. This subjective dimension corresponds to the frequency perception. The three levels "low, medium or high" are insufficient to assess the pitch. The more accurate estimates allow to distinguish two types of subjective pitch scales [4]:

- *chroma* on which all musical scales are based,
- and *pitch* on which the scale of mel is based. Figure 3.5 presents pitch variation with the frequency of a pure tone.

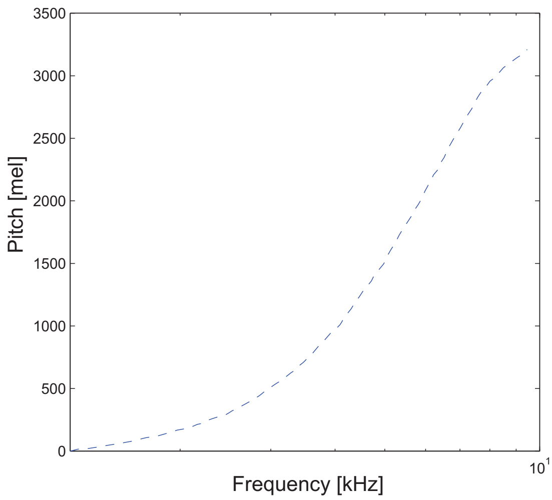


Figure 3.5: Pitch variation [mel] as a function of the frequency [Hz] [4].

These two scales are obviously concerned with pure tones. However, if one is interested in complex sounds, one will decompose the sound speaking about *spectral pitch*. In summary, the pitch of complex sounds depends essentially on the frequency of fundamental component, named *fundamental pitch* [34]. Due to their complex spectrum, the estimation of their pitch is also influenced by their timbre (paragraph 3.1.2.5).

Similarly for intensity perception, researchers focused on pitch perception. Indeed, in French Congress of Acoustics in 2010, Demany [93] and McAdams [94] presented two experiments on this topic. With a psychological approach, Demany wants to understand the psychological mechanisms which govern our sound perception. In his study he is interested in identifying our capacity to extract a reference sound among a group of different sounds (of different pitches). His results show that it is easy for people to find the reference sound in the group even if this sound is slightly modified. With a psychoacoustic approach, McAdams and Giordano are interested in the influence of the type of participants regarding pitch perception (*i.e.* if they are musicians, music lover or neither). They have been able to show that if a sounds' series is composed of different pitches, some have another kind of timbre where the notes are extracted and well recognized among the others.

3.1.2.4 Duration

Psychology distinguishes the *perceived* duration and the *estimated* duration [95] [96] [97]. The *perceived* duration refers to the fact that one believes in a full capture of all events in one go. However, if the duration exceeds two or three seconds, it ceases to be "perceived" and becomes the object of a qualitative or quantitative estimation. Psychology studies also distinguish two other concepts [98]: the *unfilled* one (a succession of brief events) and the *filled* one (a continuous sequence). Indeed, it has been shown that the *unfilled* durations are

[2] According to American Standards Association (1960), pitch is the attribute of auditory sensation in terms of which sounds may be ordered on a musical scale.

overestimated compared to the *filled* ones. To pursue in those two concepts, Geissner [99] focused on the link between the continuous assessment of an unstationary, long duration sound, and the overall judgments of some excerpts. First, participants had to continuously quantify the perceived annoyance of a long duration sequence by moving a sliding cursor along a scale. Then, they had to express their overall unpleasantness judgment for eight excerpts of the first sequence. This study has shown that by comparing the two assessments, results are similar. A link exists between continuous assessment of annoyance and local ratings. Indeed, the same annoying sound events were identified with the two approaches (a truck's departure with acceleration, reverse motion, idle, truck's arrival with braking, switching off the engine, the shock of the pallet truck and the closing of the tailgate) [100].

Various research works focused on duration perception and especially on the overall effect on another parameter (such as masking effect [101], loudness evaluation [102] or even discomfort [103] for instance). Indeed, in their experiment Griffin and Whitham [103] want to determine if the relative discomfort produced by a 4 Hz and a 16 Hz sinusoidal whole-body vertical vibration is dependent on the duration of vibration exposure. In the first part, participants adjusted the level of the "test" vibration in order to produce a similar amount of discomfort as that produced by the "standard" vibration at a level of 0.75 ms^{-2} r.m.s. Two sessions were realized: in the first one, the 4 Hz stimulus was the "standard" vibration while 16 Hz stimulus was the "test" one and *vice versa* in a second session. Results show that the discomfort equivalence is independent of duration for vibration exposures up to 36 minutes.

3.1.2.5 Timbre

Timbre allows one to determine the source's nature and to describe its characteristics such as "muffled", "dull" or "brilliant". This concept is not so easy to understand and its definition is not very clear. Indeed, Krumhansl [36] wonders in Structure and Perception of Electroacoustic Sound and Music, *"Why is musical timbre so hard to understand?"*. The scientific community is inclined to define it as "all except intensity, pitch and duration". Indeed, according to American Standards Association (1960), Pratt and Doak [104] or Mc Adams and Cunible [105] among others, timbre's definition is valid as long as loudness, pitch and perceived duration of stimuli are kept constant. Moreover, Letowski [106] gives a precise definition of it in an article in which he compares three very close concepts: timbre, tone color and sound quality. Indeed, for him, *"timbre is that multidimensional attribute of an auditory image in terms of which the listener judges the spectral character of sound"*. However, we have to keep in mind that even if the timbre is supposed to be independent from loudness, pitch and duration, they can influence its perception.

Other authors distinguish themselves bringing some variants to the timbre's definition according to chosen approach. Indeed, Wedin and Goude [107] separate *acoustical* and *psychological* definitions. The first case associates timbre's variation to physical characteristics while the other case deals with descriptions from the participants' experience. In cognitive psychology Hadja et al. [108] have also highlighted two manners to describe timbre. The first one which refers to the source (described as a *categorial* approach) and the second one which orders the sounds in accordance with their perceptive dimensions explained by the physical measures.

With a study on musical instruments' timbres, Faure [109] has shown that participants can recognize sounds thanks to descriptions made by other participants who heard the stimuli in a previous test. In a similar way, Lemaître [110] has focused on the recognition of environmental sounds thanks to vocal imitations. In fact, it has been noticed - in an experiment in which a participant had to describe a sound to another one - that vocal imitations are spontaneously used in 59.3% of the cases. Indeed, people used vocal imitations more often than verbalizations in order to describe non-well identified sounds than well identified sounds.

In another register Risset [111] and Castellengo and Dubois [112] were interested in timbre when sounds were played backward asking to people to qualify the instrument of the sound sequence. They all agree that timbre changes radically, so it is difficult to describe the source. Moreover, in their experiment Castellengo et al. precise that, the first stage consists of a recognition approach in view of a sound source.

The multidimensional nature of timbre has prompted numerous researches to describe it through dimensions and physical parameters on which it depends. Indeed, as we will see in Chapter 6, most of authors who focused on timbre perception used the MultiDimensional Scaling method (MDS) to specify timbre of instrumental sounds [113] [114] [115] [116], of automotive sounds [39] [42], industrial sources [37] or in a more general manner [117] for instance.

3.1.3 Vibrations perception

When one goes down towards the low-pitched sounds (below than 20 Hz), the loudness is gradually replaced by a tactile vibration and the ear can not incorporate this signal anymore.

Study of vibration perception is complex for one main reason: the difficulty to reproduce in detail previous studies (nature, level and dynamic of vibrations; behavior of the seat and/or the steering wheel; contact between body and seat or sensitivity of the participants). Indeed, the human body is a complex structure. Its dynamic behavior shows for some frequencies resonance phenomena which can be dangerous. Standard E90-400 [118] gives more informations - for an excitation below 2 Hz, the body behaves as a single mass and the total body is excited in the same way. Two strong resonances between 3 and 6 Hz and between 11 and 14 Hz are linked to the movement between the thorax and the buttock. Figure 3.6 highlights some resonance frequencies of organs for vertical excitations.

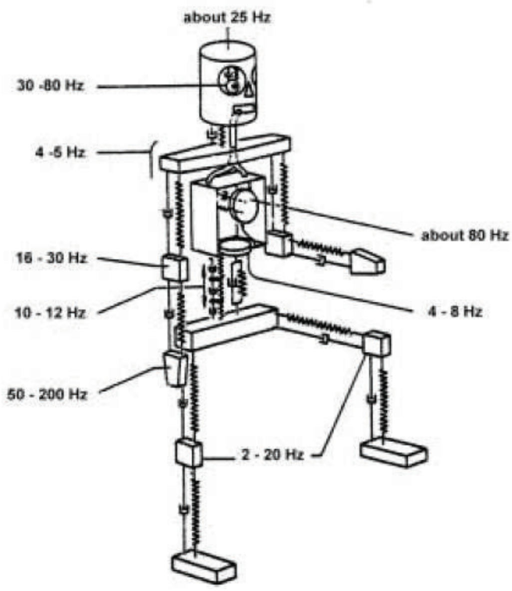


Figure 3.6: Simple theoretical model of the resonance frequencies of the human body [5].

The most well-known disorder related to the vibrations is the travel sickness. Nausea is caused by large amplitudes of vibrations that are found typically on boats for instance. Impaired vision has also been detected and linked to movements of the eyeballs.

3.1.3.1 Perception threshold of vibrations

Unlike the acoustic modality for which there are several international standards about the perception threshold, ISO 2631 [9] gives it for vibrations. In accordance with this standard, the median perception threshold is about 0.015 ms^{-2}.

Parsons and Griffin [119] have compared several adjustment methods to assess the perception threshold for vertical vibrations, and they concluded that on average people are more sensitive to vertical acceleration for frequencies above 31.5 Hz. Such frequency dependence is close to the one given by ISO 2631. Other studies led by different authors [5] [6] have allowed to establish perception thresholds of vibrations. Figure 3.7 shows the detection thresholds measured by Bellmann [6] in horizontal and vertical planes for $f < 100$ Hz.
We can notice in this figure that the body is more sensitive at low frequencies in the horizontal plane, with a perception's threshold around 0,0031 ms^{-2}. It is, however, more sensitive in the vertical plane above 3 Hz.

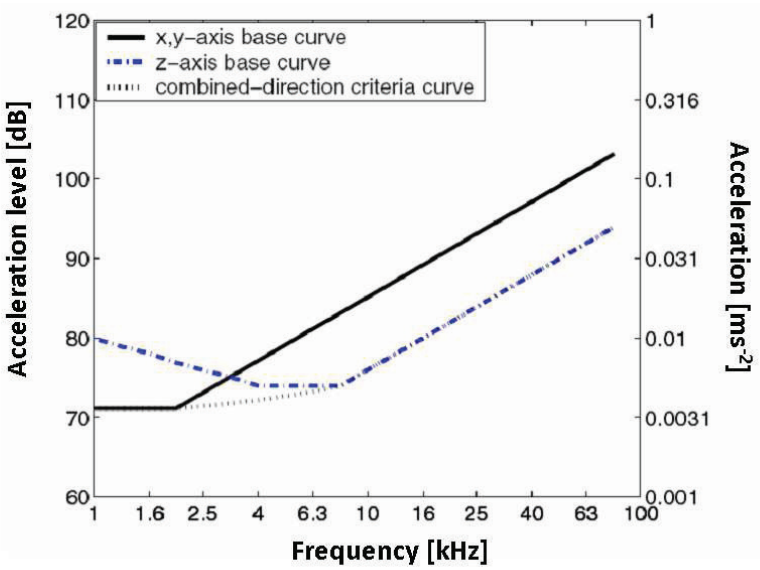


Figure 3.7: Vibrations perception threshold in vertical and horizontal planes [6].

We will note that the calculation of the acceleration in dB is done using the following equation:

$$a_{dB} = 20 * log(\frac{a_{abs}}{a_{ref}}) \tag{3.1}$$

with a_{dB}, the acceleration en dBms^{-2},
a_{abs}, the acceleration measured in ms^{-2},
and $a_{ref} = 1\ \mu ms^{-2}$.

Furthermore, Bellmann worked on the link between sounds and vibrations. He studied the perceived consistency between those two modalities for vehicles at idle along different directions, and he concluded that there is a state of "balance" to be observed between vibration intensity and sound intensity expected by drivers.

Other authors focused on vibrations perception of different body parts and in the three spatial directions ($\overrightarrow{x}$, $\overrightarrow{y}$ et $\overrightarrow{z}$). Indeed, Morioka and Griffin [120] compared in 2008 the perception's thresholds of horizontal and vertical vibrations (of body, hands and feet). Their results show that thresholds for those three body parts are highly frequency dependent and that the sensitivity differs between the three locations (body, hands or feet). For the nine axes (three axes per body part), sensitivity is greatest for vertical vibration in the frequency range of 8 and 80 Hz, whereas sensitivity is greatest for vertical vibration at the hands at frequencies above 100 Hz.

However, the perception threshold of vibrations, according to the various measurement experiments realized, the methodologies used can explain the disparity of results (AFC adaptive method for Bellmann [6] and Morioka [121] or paired comparison for Miwa and Yonekawa [122] and Parsons and Griffin [119]).

3.1.4 Multimodality

With the term *multimodality* I refer to the works which take into account, several parameters of sound, vibration and sight. Various approaches have emerged on multimodality topic: the vibration effect on the noise assessment, the effect of sound stimulus on vibration appraisal and the effect of both on the overall evaluation of a parameter (such as comfort [123]). Interaction between sound and vibration is certainly a complex phenomenon. Therefore, conclusions of the existing literature should be considered with care because they depend on different parameters used in the experiment as test protocol, stimuli reproduction or methodology/techniques of analysis results.

The common basis of those studies is the use of a bench made up a platform with a seat and sometimes even with a steering wheel linked to car industry for experiments [25] [65] [120] [124]. However, they do not take into account the same degrees of freedom. A majority limits their reproduction in the vertical plane along the $\overrightarrow{z}$ axis for the seat [46] [47] [125]. Indeed, it appears that the whole body is more sensitive along this direction. However, they conclude also that it would be interesting not to be restricted to only one direction and to take into account the others in the horizontal plane. Besides, Barth [126] suggests an answer in 2006. During his study on the perception of real and synthetic vibration signals (limited to the first even harmonics of the signal), he has noticed a significant sensitivity along the $\overrightarrow{x}$ axis of the platform. Moreover, in the same way as for reproduction of a seat's vibrations, reproduction of steering wheel vibrations is not made in the same manner for the different experiments. His general conclusion is that the steering wheel's influence should not be overlooked because it can contribute strongly to the vibration perception, especially beyond 100 Hz.

Concerning sound reproduction in experiments which focus on this topic, the system also differs with headphones, headphones and subwoofer, loudspeakers or loudspeakers and subwoofer. The use of headphones is a good alternative in order to mask the noise generated by the electrodynamic exciters which reproduce vibrations. Concerning the subwoofer, it helps to reproduce the low frequencies felt by the body [127].

In this section, we are discussing the multimodal aspect through four configurations vibrations then visual impacts on sound perception (3.1.4.1 and 3.1.4.2), sound influence on vibration perception (3.1.4.3) and finally contribute both on a third parameter (3.1.4.4).

3.1.4.1 Vibrations impact on sound perception

Various research teams have investigated vibrations influence on the sound evaluation. Indeed, Paulsen and Kastka [128] have been interested in noise perception by proposing to participants 16 combinations of vibrations (in $\overrightarrow{z}$ direction) and noise coming from tram recordings. Results show that noise perception is strongly influenced by simultaneous vibration. Indeed, 37.5% and 75% and then 87.5% of people report noise perception (for combinations of v1/n0, v2/n0 and v3/n0[3], respectively). This can be explained by the fact that the vibrating apparatus emits noise of 33 dB(A) when producing the third (and strongest) level of vibration. In the same way Parizet et al. [26] showed a slight influence of vibrations on sound perception too. Indeed, taking into account sound and vibration this team was interested in the following question, *"can the presence of a modality modify the perception of the other one?"*. Moreover, they precise that it would seem that seat and steering wheel vibrations have an equal importance for participants. Also, by focusing on loudness appraisal Parizet et al. [125] [129] arrive at the same conclusion. The estimation of loudness magnitude of a tone, compared with a reference tone heard without vibration stimulation, is not influenced by vibrations, neither for 28 Hz nor for 1000 Hz tones. In the same topic Merchel et al. [130] have presented to participants sound stimuli and same sound stimuli with tactile stimulations. The experiment's task consisted of adjusting level of a sound signal of the vibroacoustic stimulus until it was perceived as equally loud as a reference sound signal without vibrations. This adjustment was repeated for four frequencies and three levels of vibrations. Results have shown that without vibrations, no difference between reference and adjustable tones was observed, whereas with vibrations the test tone was adjusted 1 dB lower. According to statistical analysis the influence of acceleration level on loudness perception was significant.

The different studies realized on vibration's impact on sound evaluation do not conclude in the same way in accordance with studied parameters (perception's threshold or loudness issue). As we have already said, comparisons of different works realized on the association between sound and vibrations are really difficult because lots of parameters of experiments play an important role in the discrepancy of results.

3.1.4.2 Visual impact on sound perception

The various studies which have focused on the influence of visual modality on sound perception principally concern loudness assessment. Indeed, Böhm et al. [131] try out the images' influence (in motion or not) on the evaluation of trains' loudness. Pictures of trains fixed or in motion are presented with the sound simultaneously. Results show that when they add an image of a non-stabilized train, participants underestimate loudness by almost 5%, compared to the case without picture. For Höger and Greifenstein [132] a similar vehicle picture was the study's parameter. They conclude that sounds associated with pictures of big trucks are considered

[3] Four levels of vibrations and four same levels of noise have been presented during the experiment (0: no stimulus, 1: low, 2: medium and 3: strong stimulus). All possible combinations are presented to the participants. For instance, v1/n0 corresponds to the first level of vibration without noise.

stronger than for the same sounds combined with pictures of smaller ones. Finally, the color has also concerned scientific works with team of Patsouras et al. [133] and Fastl [134]. They have shown that with a picture of red trains, the sounds are perceived louder than with pictures of green ones. All those studies thus show an influence of visual context on the assessment of loudness. However, some exceptions occur with the studies of Menzel et al. [135] [136] and of Parizet and Koehl [137] where no influence is observed. For Menzel the influence of red/green colors on the loudness assessment was not revealed. He suggests a possible explanation of those divergences with other studies cited above. The first parameter would be the methodology used. It therefore appears that a method with psychoacoustic spontaneous loudness judgments is better fitted to study interactions between vision and sound. On the other hand Parizet and Koehl replicate the experiment described by Patsouras et al. [133] or Rader et al. [138] and they do not find any influence of color on the loudness assessment (contrary to the two other teams). However, the discrepancies can be explained by different parameters: the cultural difference [139] or the small number of participants.

As part of studies related to the automotive industry, other themes, in addition to the assessment of loudness have been discussed. One of them, important for the sound quality of vehicles, concerns the visual impact on the evaluation of power and sportiness. Indeed, in 2006 Ellermeier and Legarth [140] presented results on such experiment. They combined pictures of sporty and non-sporty cars to sounds of accelerating vehicles. They conclude that the bias induced by the image has a similar effect to a variation in sound level of 2 to 3 dB on the sportsmanship's assessment. So, a vehicle's picture has a strong influence on the judgments of sound quality. Participants integrate the visual modality in their assessments even when they are explicitly asked to evaluate the auditory modality only. That is what Bézat [81] concludes when she focuses on the doors closing sound. The image (here using a video) slightly modifies the perception of quality for this kind of sounds. A bad quality picture would deteriorate the perception of a good quality sound and *vice versa*. Also, as part of his PhD thesis, Amari has dealt with influence of visual context on comfort evaluation. He has worked in two different manners. The first one [45] focused on visual conditions' influence on the overall comfort assessment of interior noise of 4-cylinder vehicles at 30 kph. This assessment has been performed with an absolute rating using a 5-point scale from 0 (not comfortable at all) to 100 (very comfortable). Results show that sight leads to a *"infinitesimal"* (according to Amari himself) positive translation of comfort scores. It also allows a better discrimination of vehicles. The second experiment [141] is devoted to the influence on the type of visual context. Stimuli are identical to those of the first experiment. The work chosen here is to exaggerate the context in which participants belong. Three different visual scenarios are diffused: country rough road (R1), new road surface without irregularity (R2) and finally sharply damaged road surface (R3). The difference of opinions between the roads two by two are not significant ($p < 0.05$), although the effects of visual context clearly reflect the participants' expectations with regards to driving situations presented. Indeed, the presentation of an *a priori* comfortable situation (R2) leads to a more severe scoring.

To conclude, visual context's effects depend on many parameters because its influence varies from one experiment to another one. Anyway, its influence must be kept in mind before designing a new experiment.

3.1.4.3 Sound impact on vibrations perception

Parizet et al. [125] [129] have led various experiments in interaction between sound and vibrations. Concerning sound influence on vibration perception, we are going to evoke two different studies. First, in Forum Acusticum in Hungary [125] Parizet et al. presented their experiment. A 28 Hz vertical vibration reproduced using a rigid chair at six different levels. Two different sound stimuli (of 1000 Hz and 28 Hz) were produced by headphones for the first and by a subwoofer for the second. Results show that vibration level's estimation is significantly influenced by the level of the 28 Hz pure tone. Moreover, they add that a *"synergistic effect"* exists - the higher the noise level, the higher the vibration level is considered. The authors conclude that it can indicate an interaction between the perception of low frequency sound by the body. In a same register with the influence of sound on a vibration level assessment (vertical and horizontal), Miwa and Yonekawa [142] presented to participants several Diesel vibrations stimuli at different levels with or without sound. The authors successively examined the effect of changes on noise and vibration level on the vibration assessment and concluded that no significant effect of sound appears on the appraisal of vibrations. As for previous studies of Parizet et al., only the highest noise level leads to an overestimation of vibration level of 1.5 dB.

Most specifically several studies evaluated sound's impact on vibration perception thresholds [6] [143] [144]

[120] [145] [146]. Indeed, Bellmann [6] and Weber et al. [144] performed at two years apart a similar study on the vibration perception thresholds (absolute and differential). Stimuli were presented with a white noise of 68 dB(A) and of 69 dB(A), respectively. The methodology was 3 AFC 1up-2down with similar stimuli levels and vibration bench. Only frequency range differed slightly from 16 to 200 Hz for Bellmann and from 12 to 80 Hz for Weber. In both cases the results obtained are very close to the literature with one small exception at 80 Hz for the first study and 63 Hz for the second one. Weber's team concludes that the noise influence was very low on absolute threshold (+1.6 dB on average) and was insignificant for the JND. On the other hand Bellmann observed no influence of the acoustics component for both types of thresholds. Also, the experiment led by Zöller and Attia [143] focused on vibration perception threshold of brake pedal vibration and the effect of noise on it. The participants' task consisted of indicating if they felt a vibration on the brake pedal or not. In the same study, they were interested in sound's influence on this vibration threshold. With four kinds of auditory signals (white noise, band-limited noise to 200 Hz, background noise recorded from a real vehicle with prominent engine order around 70 Hz and 140 Hz), results show that median vibration thresholds are not significantly different. There is no sound influence on vibration perception. Moreover, results prove the frequency dependency of the vibration threshold. This conclusion is in good agreement with a study of Morioka and Griffin [120], which measured vibration perception thresholds for vertical foot vibration in normal upright sitting posture and with ISO-2631 [9]. Also, even if these results do not have the same conclusions as those obtained by Sueki et al. [145], conclusions are closer to Bellmann's conclusions [146] which report no effect of pink noise on the vibration threshold for whole-body vibration, except for a vibration frequency of 63 Hz. Also, this topic has been studied at Renault by Barth [126] in 2006. He was interested in sound's influence on vibration perception with different combinations of vibrations ($\overrightarrow{x}$ direction of the platform and $\overrightarrow{x}$ and $\overrightarrow{z}$ directions of the steering wheel) and sound signals. Results show that sound signals do not change vibration perception. However, it may be noticed that participants perceive level changes in vibration stimulation. There is significant sensitivity along the $\overrightarrow{x}$ axis of the platform. Therefore, even if this direction is the only one reproduced on the bench, it seems that only the $\overrightarrow{z}$ axis of the platform is insufficient in the literature .

3.1.4.4 Vibration and sound impact on another parameters

Other kinds of studies focused on comfort (or discomfort) assessment [26] [48] [121] [124], especially for idle driving situation [25] [26] [27] [46] [65] [120]. It has been observed that both modalities can contribute equally to comfort until one becomes highly dominant [26]. The overall sensation seems to be dominated by the most annoying or strongest modality. Besides, Bellmann [6] concludes that there is a state of "balance" to be observed between vibration intensity and sound intensity. Indeed, Leatherwood [123] has showed that the contribution of each modality depends on their respective levels. But their interaction is clear [25]; for vertical vibration levels which negatively affect the comfort, the addition of a sound has little influence. However, with a weak vibration level increasing noise level noticeably raises the discomfort assessment. Here the authors join here the idea of "balance" between the term used by Bellmann [6] during an automotive study and the one mentioned previously. Moreover, the comfort issue is a scientific topic often treated in the transportation domain (automotive and rail industries). Parizet et al. [26] and Howarth et al. [48] are two examples of this kind of studies. Indeed, the first one has realized an experiment in three stages: the discomfort's assessment of a sound stimulus alone, the discomfort's assessment of a sound presented to the participants with a vibroacoustic stimulus and finally, global discomfort's evaluation of the vibroacoustic stimulus. For some participants, the overall annoyance is only related to vibrations while for others, it seems to be linked to both modalities. In their study, Howarth et al. [48] focused on the discomfort evaluation caused by sounds and vibrations generated when a train passes close to a domicile. They conclude that vibrations do not affect the annoyance rating. Conversely, noise influences discomfort appraisal due to vibrations according to the relative magnitude. Therefore, discomfort caused by low vibrations decreases for higher noise levels and global discomfort is linked to relative levels of noise and vibration stimuli. Finally, Paulsen and Kastka [128] conclude that the overall evaluation of annoyance is dominated by the noise which was revealed as being highly significant.

Therefore, some studies show the influence of sound and vibration modalities on their perceptual properties, but the effects of interactions are either insignificant or very low. For comfort (or discomfort) appraisals all researches seem to agree with the role played by sound and vibration in global assessments. However, if all these effects turn out to be significant, then they remain very low and give some divergent results [147] [148] with current International Standard on vibration [149].

3.1.5 Intercultural approach

As already mentioned in the introduction of this chapter, culture contributes to the perception of the surrounding world. However, Hansen highlights in 2009 [150] that the main difficulty related to intercultural studies lies in the fact that it is important to investigate how different cultures perceive sound with respect to noise metrics which are used to establish international noise evaluation standards.

In the case of studies on automotive noises, differences between Austrian, Italian, Russian and Japanese people have been revealed during an evaluation of sound annoyance for various driving situations [31] (steady ones with idle, 3^{rd} gear at 50 kph, 4^{th} gear at 70 kph, 4^{th} gear at 100 kph and 5^{th} gear at 130 kph, and unsteady ones with 2^{nd} gear and 3^{rd} gear Wide Open Throttle). Japanese and Russian people on the one hand and Austrian and Italian on the other hand obtain similar results. This leads to the hypothesis that the annoyance perception of vehicles' interior noise is different between Europe and Asia. Moreover, Hussain et al. [31] conclude that differences in subjective perception of vehicle's sound quality depend on driving situations. They also advise to use at least three different driving situations in order to analyze intercultural differences. Other judgment differences about car noises between Europeans and Japanese, have also been emphasized by Shibuya's team [30].

Concerning France/Germany comparisons (countries particularly interesting to my work), Renault has already conducted projects on this topic [28] [29] with a study on Diesel vehicles. The vehicle trials realized in a real context allowed to answer key questions which distinguish the two markets:

- the first difference is concerned with the *driving style*. The "cool" driver (far from the steering wheel with only one hand on it and often in undershoot engine) is more represented in France. The "sporty" driver (fast driving with two hands on the steering wheel and in overshoot engine) is the majority represented in Germany;
- the second difference is concerned with the *gender*. If men know many things about vehicles, women seem to be more and more loquacious;
- the third difference is concerned with the *vehicle type*. Transversally, it has been observed that the engine's performance is mainly made through kinesthetic and audio channels. The predominant behavior is the "driving by ear". Similarly, the noise, vibrations are considered necessary in order to "drive and feel the car". In the majority, vibrations are felt through the gearshift lever, steering wheel and pedals, then through the seat, the cabin and the suspension. Finally, the engine sound does not appear to be the first choice criterion. It can be a qualifying parameter if power is insufficient but it does not itself determine the purchase decision. The customer gives priority to the overall car impression.

Therefore, despite weak divergences, the French and German's agree with the expectation of a vehicle and its engine.

In addition to works about cultural differences, comparisons between expert/naïve[4], male/female, and young/older are sometimes raised [151]. By comparing Japanese amateurs, Japanese professionals and US professionals for an evaluation of Diesel exterior noise at idle, Hashimoto and Hatano [33] concluded that Japanese professionals judge the sound more impulsive compared to Japanese amateurs and US professionals[5]. Although this same team could find some differences in the evaluations, they also found many similarities between the three groups. As a consequence we have to take care of the different results between various studies. Each of them consists of a particular case. During another experiment detailed in Psychological evaluation of noise in passenger cars: Analysis of different group of subjects in nationality, age and gender in Contributions to psychological acoustics [152], noisiness and timbre evaluations of vehicle interior sounds were compared among groups of participants with different nationalities, genders and ages. Indeed, all participants were attended the International Congress of Applied Psychology of Kyoto in 1990. Many different nationalities were represented with people from USA, Japan, Netherlands, Italy, UK, Germany, Belgium, France, Spain, Finland, Sweden, Norway, Australia, South Africa, Iran, USSR, Yugoslavia, Israel, Iraq, Mexico and China. The study's results show that American people judge stimuli as being more noisy than European participants. The same conclusion

[4] For "experts", I designate people working or having worked in the field related to the experience in opposition with the "naive" ones, qualifying people having little even none of knowledge in the field involved.

[5] "Amateurs" and "professionals" terms are used in the same way as "naïves" and "experts".

is given for female and elder groups for whom the stimuli are more noisy than for male and younger people.

Studies mentioned above conclude that beyond a cross-country difference, this is mostly an inter-continent difference which is the most important in subjective judgments.

3.2 Sound quality

In "How many psychoacoustic attributes are needed?" presented in Acoustics'08 Congress, Pedersen and Zacharov [153] gave two definitions which distinguish the character and the quality of a sound:

- "*character of sound: the overall concept of a set of characteristics that portrays the sound. The sound character can be specified by a number of attributes and/or metrics. The sound character is not to be confused with the sound quality which involves a comparison with some desired features*";
- "*quality of sound: assessment of quality involves a (conscious or unconscious) comparison with some desired features (a personal reference). For that reason, quality is a subjective characteristic. The better the characteristics of the sound match the desired features, the higher the quality will be rated. The sound quality is not to be confused with the sound character*".

Indeed, sound quality is based on human perception which does not only depend on the listener's ears but also on other sensory modalities like visual, tactile or haptic information.

In this part, we focus on some useful and commonly used indicator definitions (paragraph 3.2.1) and test methodologies (paragraph 3.2.2).

3.2.1 Psychoacoustic indicators

The press sets out to define the notion of an acoustic score in surveys of the vehicle's judgment [154]. In general the scores are based on the calculation of dB(A) in different driving situations, named standard situations[6]. However, recently, new concepts to judge the sound quality emerged in the automotive press. The scientific community is working with the industrials to define synthetic indicators reflecting the sound quality perception. From a scientific point of view defining an acoustic score correlated with participants' perception sums up to predict a subjective quantity by linear regression on the set of objective parameters. I choose to present here three of these indicators (the most known and used): loudness, roughness and fluctuation strength. Although they are supposed to describe different aspects of sounds, those parameters are not completely independant.

3.2.1.1 Loudness

Loudness and equal loudness notions are products of Psychoacoustics (paragraph 3.1.1.2), result of the sound intensity encoding by the hearing system, proper to each person. As already detailed in paragraph 3.1.2, this is an important indicator for environmental noise field. The model proposed by Zwicker in 1960 has been improved (Zwicker and Fastl, 1983 [155] and Zwicker et al., 1985 [156]) and extended in recent years, including its applicability to impaired persons [157]. Today, efforts continue to develop a measurement tool that allows an easy and reliable measure [158]. Although primarily related to sound intensity, loudness depends on cognitive functions and seems to be difficult to grasp. Thus, Susini [159] was able to show the influence of the recency effect[7] and memory effect at least for the overall loudness of an instationary sound if not for the instantaneous loudness. But this type of sound is common in our environment.

[6] 2s at idle engine running, a city sequence at 50 kph in the 3^{rd} gear, highway sequence at 90 kph in the 5^{th} gear, a mountain portion with a damaged road surface, and finally a highway sequence at 140 kph in the 5^{th} gear.

[7] Recency effect refers to the ease to remember the last items of a stimuli list. During experiments, Postman and Phillips (1975) and Glanzer and Cunitz (1966) presented words' lists of different lengths to participants. They asked them to recall the words that they remembered in the order they wished. When one asked them immediately after, the first and last elements of the list were most likely to be recalled while few people remembered the middle of the list. When one asked them 15 or 30 seconds after, only the beginning of the list had a high probability to be listed. The authors interpret these experiences as a proof of a short-term memory exclusively responsible of the recency effect.

Loudness allows us to say whether a sound is loud or not. The relationship between sound intensity and loudness depends also on the frequency and spectral width of complex sounds. If one wants to have a direct measure of the perceived sound level, it is necessary to construct a subjective scale with proper units taking into account the variation in sensitivity of the auditory system according to the sound frequency (cf 3.1.2). This indicator's unit in sone (equation 3.2) or in phon (equation 3.3) is:

$$S = 2^{(\frac{P-40}{10})} \tag{3.2}$$

$$P = 40 + 10 * log(S) \tag{3.3}$$

with S, intensity in sone,
and P, intensity in phon.

As already said in 3.1.2.2, we attribute a loudness of 20 phon for a sound which is perceived as the same level as a 1000 Hz pure tone at 20 dB. With this definition (equation 3.2), the loudness in sone is the perception level of a 1000 Hz sound at 40 dB. 2 sones then represent the level of a perceived sound twice as loud and so on. Figure 3.8 presents some examples of the correspondence between the two scales.

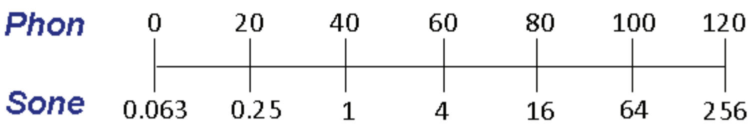


Figure 3.8: Correspondence between phon and sone scales.

The sone scale has been established from a method named the *direct method* (Stevens, 1956) whereas phones scale came from a *comparison method* (Fletcher et Munson, 1933). Today, several models allow the computation of loudness of stationary sounds. The LMA[8] team has been interested in the comparison of some of these models [160]. It has shown that for stationary sounds' loudness, all models give a very good estimation. Concerning unstationary sounds, calculation has not been validated clearly on environmental sounds yet. The overall loudness applied to unsteady sounds can be calculated by indicators such as N5, N10 or STLmax[9]. However, the weighted levels do not reflect the ear's mechanisms which impact sound perception like frequency masking (cf 3.1.2.2).

In the automotive field this indicator is commonly used. Even today this criterion has been the topic of various studies. Loudness's *measure* is more often based on software progressively developed by the teams of Zwicker [161] in Germany and Moore [162] in England. The more recent versions, suitable for steady signals, give loudness assessments close to results obtained with subjective measurements in the laboratory. They are relatively reliable for steady stimuli. However, more and more research topics focus on loudness evaluation of unsteady ones [163] [164]. Indeed, during his PhD work Susini [163] realized different experiments on loudness appraisal of acceleration phase coming from vehicle recordings. He used two kinds of evaluation: a continuous judgment and a global one. Participants of experiments evaluated each unsteady sound by associating at each moment a force equivalent to the perceived loudness. In short, they used a stylus in order to "draw" a loudness evaluation[10]. In a second task they were asked to evaluate the overall loudness at the end of stimulus. Results of these evaluations showed a strong correlation between the signal's end in the continuous judgment and the global judgment (the recency effect, mentioned above, can explained this result). Moreover, this correlation is even stronger than the signal's end corresponding to the maximum of continuous evaluation. Briefly, to calculate

[8] Laboratoire de Mécanique et d'Acoustique de Marseille, France.
[9] N5 and N10 [161]: in a generic way, indicator Nx represents loudness value exceeded during x percent of time (Zwicker and Fastl, 1999). The authors suggest to use it for environmental sounds.
STLmax (Short-Term Loudness) [162]: indicator which allows to calculate maximum of short-term loudness to estimate overall loudness of time-varying sounds (Glasberg and Moore, 2002). STL represents loudness perceived at each instant.
For more information: http://www.genesis-acoustics.com.
[10] This methodology has been used by Saint-Loubry [15] in her work about sporty sound of gasoline vehicles also.

the overall loudness of a sound sequence, one has to take into account not only emergence level (Kuwano and Namba [165] and Fastl et al. [166]) but also their position in this sequence (Susini et al. [167]). In the case of unstationary sounds which increase or decrease continuously (like acceleration or deceleration for instance), the loudness varies over time. However, the final loudness of a sound ranging from x to x-n dB is less than the loudness of a sound at x-n dB. This phenomenon is called “decruitment” [168]. The opposite phenomenon may also occur with a smaller difference in loudness.

3.2.1.2 Roughness

Roughness corresponds to an amplitude modulation of an acoustic signal. It is a basic psychoacoustical sensation for rapid amplitude variations which reduces the sensory pleasantness and the quality of noises. The experiments of Helmholtz on perception of pure tones concludes with the following results (recalled by Pressnitzer [169]). A *beating* phenomenon appears with modulation frequency f_{mod} from 15 Hz to 300 Hz (frequency range highly sought by engine rotation). However, the perception of two tones with equal amplitude frequencies f_1 and f_2 highly depends on the frequency difference $\Delta f = f_2 - f_1$. At low frequency differences ($\Delta f < 15$ Hz) a single tone is perceived with a fluctuating loudness and a pitch which corresponds to a frequency of $f_1 + \frac{\Delta f}{2}$. The fluctuation rate is equal to the frequency difference Δf. Also, by increasing the frequency difference, the beats are accelerating. Beyond around 15 Hz fluctuations vanish and their perception becomes blurred. Nevertheless, Helmholtz precised that one continues to have consciousness of the presence of these fast beats. This gives the roughness impression. This roughness sensation is maintained up to higher frequency differences of about critical bandwidth until the two tones become separately audible.

Sensitivity to roughness depends on the carrier frequency f_t, modulation frequency f_{mod}, modulation index m and presentation level L_p. In accordance with the classical definition of roughness, a 1 kHz sine wave tone at 60 dB(SPL) whose amplitude is modulated with a modulation frequency f_{mod} of 70 Hz and with a modulation index m of 1 is allocated a roughness's value of 1 asper. Two best-known models for calculating the roughness are the Aures' one and the one of Daniel and Weber [170]. Those two models take a leaf out of Zwicker's model concerning loudness calculation.

Roughness is a psychoacoustic attribute in which the automotive industry is interested. Indeed, roughness is often associated with sporty engine noise [171] [172]. The broadband spectrum of engine noise makes roughness' estimation difficult. Still in this domain, Lowet et al. [18] have developed a metric to quantify the irregularity perception of Diesel engine sounds which were then validated by a listening test. It has been observed that irregularities can contribute to a very different timbre. They investigated several hypothesis about different parameters like the influence of the sound level, the number of irregular events and the engine speed to understand the perception of irregularities. The results show that mainly irregularity level, signal level, irregular event number and engine speed are important in the roughness perception. Thus, an engine which knocks with large regular amplitudes may be considered less noisy than an engine with large irregular amplitudes. Moreover, Feng [173] says that the roughness of the sound of an engine, as well as its quality in general, has a good correlation with the engine harmonics.

In a same way, Martner and Zebs [174] have worked on a psychoacoustic model for the prediction of accelerating roughness conditions. Participants have indicated their current impression of roughness by moving a cursor on a computer screen continuously along a linear visual scale labeled smooth to rough. The results show that the model gives promising results to predict the time-varying roughness. It, also, concluded that perceived roughness is important for overall preference.

3.2.1.3 Fluctuation strength

Fluctuation strength is a perceptual quantity which describes the slow amplitude modulations. It has been introduced at the same time with roughness. According to Zwicker [161], a 20 Hz modulation is considered as a transition threshold between fluctuation and roughness. The best-known example in order to illustrate this attribute is linked to speech. Its fluctuation of about 4-5 Hz corresponds to the frequencies for which the ear is the most sensitive. The fluctuation's unit is the vacil. One vacil corresponds to a pure tone of 1 kHz, 100% modulated, with a modulation amplitude of 4 Hz and with a noise level of 60 dB.

So, like roughness, fluctuation strength describes temporal variations of sounds. While fluctuation strength is elicited by slower variations up to about 20 Hz, roughness is perceived at faster variations. However, there is no strict boundary between both psychoacoustic magnitudes. For example, sounds with temporal variation of 25 Hz produce fluctuation strength *and* roughness. Actually, most warning signals used in daily-life are characterized by large values of fluctuation strength.

3.2.1.4 Conclusion

These are the three parameters which have been presented since they are the main descriptors that have explained the sound and vibroacoustic spaces of the Diesel vehicles. Indeed, we will see in Chapter 8 that the loudness is the main psychoacoustic descriptor that differentiates Diesel vehicles during unsteady driving situations.

As for the roughness or the fluctuation strength, we have seen that these two psychoacoustic parameters are linked together since they describe a modulation as being more or less pronounced. Nevertheless, we will see in Chapter 6 that the two parameters that differentiate the Diesel vehicles during steady driving situations are specifically the modulation frequency and the emergence. The modulation of amplitudes covers a broad domain of frequencies and "fills" the space between fluctuation strength and roughness. Indeed, the modulation frequency, the modulation depth and the modulation amplitude are the acoustic parameters which describe the physics of the modulated signal envelope. The different steps for calculating the modulation frequency by Artemis 10[11] includes a Butterworth filtering to extract the octave 1000Hz, the calculation of the Hilbert transform and the FFT of the envelope. During the data reduction, the calculation of this parameter was made on different octaves: 1000, 2000 and 4000 Hz. The results showed that the octave 1000 best explains the sound space of the steady driving situation.

Concerning the emergence, it is an indicator which is not purely a psychoacoustic parameter because it does not take into account psychoacoustic notions such as masking or the critical band, for instance. However, it is used in order to find some noise components which, because of their emergence, may give a tonal character to the stimulus. The calculation of this parameter by Artemis 10 gives an emergence criterion of the noise in the signal. It determines the power of a frequency band of an 1/3 octave, which is then reported as the average power in several bands of 1/3 octave. The higher the value is, the greater the number of tonal components in the signal. The analysis of the specific emergence ratio allows a detection of signal resonances.

3.2.2 Test methodologies used in Sound Quality

The general sequence of events of a sound quality study is as follow:

- build a sound database for experiments (noise and vibrations perceived inside the cabin in our case);
- determine subjective criteria *via* subjective tests performed in order to ensure statistical stability of results;
- determine objective criteria for signals,
- look for correlation between objective and subjective criteria.

But in order to start a subjective experiment, the first question to answer is, which kind of methodology should be used? What experimental protocol, which stimuli reproduction, and for which kind of people? These are the many questions that we need answer before the preparation of the test. Lots of methodologies are used in the scientific domain with a particular purpose for each of them. We explain, in this paragraph those used during this PhD work.

Psychoacoustic experiments allow us to express subjective judgments about the stimuli studied. It is no longer here to refer to the measurement systems but to use the human to assess the stimuli. The main difficulty in developing any psychoacoustic test is:

- choosing the most appropriate experimental protocol in connection with the question of the test (we will remember also the by-word "one test = one question");
- taking into account the potential biases included in the chosen test (instruction [175], real situation or in laboratory [66], intercultural differences [11] or also multimodal interactions [26]).

[11] Software of Head Acoustics.

3.2.2.1 Instruction

Before starting any test an instruction is given to each participant. It allows us to:

- put the participant in the situation (to install him comfortably, to precise him about what state of mind in which he must be);
- give him test instructions in order to explain the purpose and the task (without giving too much away)[12];
- summarize how the test happens (number of parts, optional break or not, ...),
- make the participant confident by saying to him or her that there is no right or wrong answers[13].

This step is also important because it is preliminary to any subjective experiences. Besides, Susini et al. [175] has worked on the importance of the instruction given to participants. Focusing on the influence of three types of instructions given at the beginning of the test (neutral, with text and visual), the results of experiment show that the addition of text and/or image is better for the understanding. Also, for the immersion sensation in vehicle:

- the addition of an image has a positive impact on the sound quality judgments,
- the addition of text and/or image changes the difference between vehicles (87% of people is more concentrated on the stimulus with the neutral instruction);
- the addition of text makes the participants more confident in their judgments (87%). The image has less influence (33% more confident). Without text the confidence rate is equal to 80%.

The neutral instruction seems to be better because it guarantees a reliable judgment of sound quality and allows an optimal discrimination between vehicles.

In the same way, the questionnaire's writing appeared to be an important and difficult step during the test's preparation.

3.2.2.2 Questionnaire

At the beginning of the thesis a first approach was chosen in order to evaluate the "Diesel reputation" in 2008 (Chapter 1). The first methodology used was a questionnaire [10] (Appendix A). Besides, different articles explain the hard task of building a questionnaire [177] [178] [179] [180] [181]. Indeed, different parameters such as the rating scales or the order of questions were considered by Howarth et al. [177]. The survey developed for this study employs both numerical and semantic rating scales. Moreover, according to Howarth et al. and Skinner et al. [181], filter questions contribute to bias social survey results. Besides, two teams recommend to minimize the use of filter questions. They also suggest that questions on a general noise may elicit more accurate responses when preceded by questions on specific noise sources. The Howarth's team applied this advice with some questions on sensitivity to noise and vibration placed after questions on ratings of vibration and noise. These techniques allowed them to avoid any influence of sensitivity questions on the ratings of studied parameter.

However, we can precise here that the questionnaire is also a methodology rather chosen to complete another one. All tests performed during my work took place with a questionnaire (the first nine questions of the questionnaire of Appendix A) or an interview at the end in order to collect information about participants (anthropometric data, type and model of their vehicle, etc.) and comments about the test (usually free verbalizations). Concerning free verbalizations (oral or written), Parizet [27] shows that in general the analysis of such verbalizations provide information on the participants' perception in multimodal situations.

Instead of a questionnaire an interview can be conducted also at the end of experiment. By *interview* term two different things can be understood: an interview in which same questions as in questionnaire are directly asked to participants or an interview during which we can directly discuss their results or their behavior. Indeed, the first provides more explanations about the meanings of verbalizations used. The second can confront persons with their results and in the same manner allow more precision on sensations. Tardieu [90] used this last technique during his PhD work. In fact with his study on sound information in a train station

[12] The participant is active in any subjective assessment. It will be even more in some experiments than in others, depending on the test methodology chosen. Bodden precises [176] that *"the motivation and the self-confidence of the subject increases while the stress is reduced"*, notably in the exercise of individual test (paragraph 3.2.2.5).

[13] In my case, my instructions always ended thus: *"There is no wrong answers, each one is a right answer"*.

he checked with participants behavior in the train station thanks to a video. They were able to discuss about why they were lost, why they did not understand the message with such sound, etc.

I will not stay for ages on the questionnaire's development because, as mentioned before, this methodology has always been used for my work as a complement to other more sophisticated methodologies.

3.2.2.3 Classification

In this type of experimental task, the participant has to categorize by taking into account all stimuli presented. He must choose his own ranking criteria. The task is to group stimuli according to their similarities and, thus, to separate them according to their differences [91] (Figure 3.9). The major advantage of this method is that it involves essentially perceptual processes. After the categories are made, the participant is asked to verbalize about each group. This second step helps to find words to express the individual perception and to describe semantically the categories. Verbalizations help to understand the foundations of different groups. Data reduction of verbalizations during my different experiments were analyzed in this way:

1. for each category, we collect associated verbatim,

2. for all verbalizations, a semantic analysis is performed (cluster of synonyms thanks to free software[14]). This allows us to obtain subjective descriptions emitted by the interpretation of the participants;

3. for each category, we sum the occurrence number of each description. By dividing this number by the sum of occurrences of the same class, we obtain the percentage of each description for each category.

Moreover, in some studies participants are even asked to choose the most representative stimulus in each category.

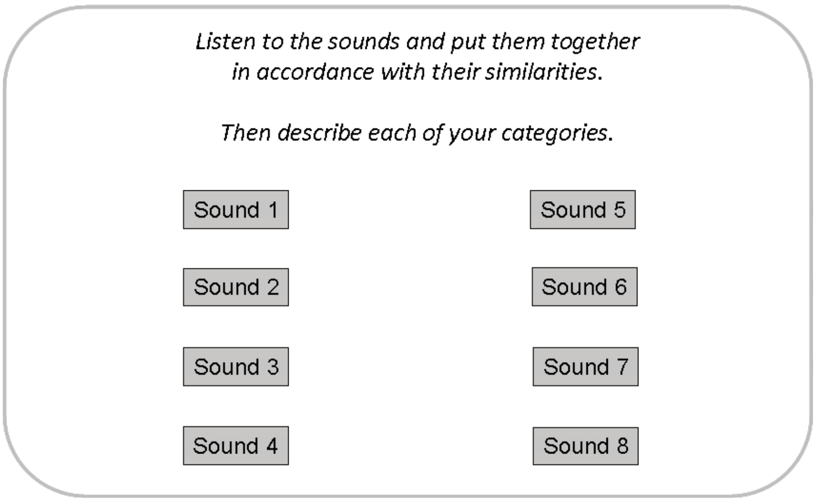


Figure 3.9: Example of 8 sounds presented to participants for the classification task. The person has to move the sounds in order to form his own categories.

Also, verbalizations can be used to choose adjectives in a later experiment like one with a semantic differential method (where the stimulus is evaluated on a scale with pairs of antonym adjectives) or one with a paired comparison method (*"between two stimuli presented, which is the most suitable to describe the adjective proposed?"*). Most of current studies on perceptual engine sound use the semantic evaluations method. A sound could be pleasant, sporty, tonal [182], uncomfortable or metallic [183], low-pitched, rough or even modulated [184].

[14] http://www.crisco.unicaen.fr (University of Caen).

3.2.2.4 Direct evaluation

In this kind of test, sounds are presented one-by-one to the participants. For each of them people must evaluate it after having listened once or several times the stimulus. Two types of scales can be proposed: a continuous scale (from *does not evoke a Diesel engine sound at all* to *evokes a Diesel engine sound perfectly* concerning my work in Chapter 5 and Chapter 7) or a divided one (with 5 or 7 equally distributed intervals in most cases). Evaluation of sound is realized by moving a cursor along the scale. Each assessment gives a score provides relative results between the different stimuli.

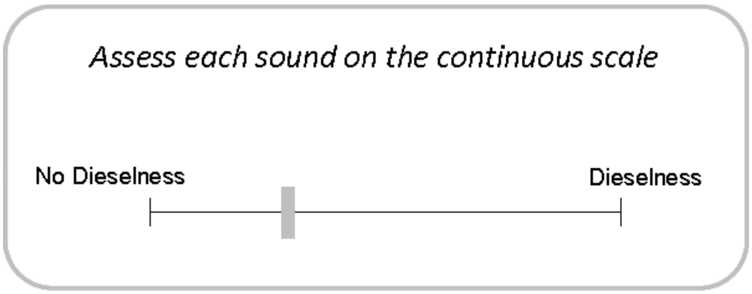


Figure 3.10: Example of a direct evaluation.

In 2005, Parizet [185] compared different kinds of test procedures including one with others, such as paired comparison (cf paragraph 3.2.2.5) or magnitude estimation for instance (not evoked here because we did not use it).

3.2.2.5 Paired Comparison

In this kind of task, stimuli are presented by pairs, in a random order, to participants. The participant has to select the stimulus which best fulfills the questions as *Which sound is louder?* or *Which sound do you prefer?* for instance (Figure 3.11). This is the most popular relative method but with the biggest disadvantage for an application in industrial environment being its long duration.

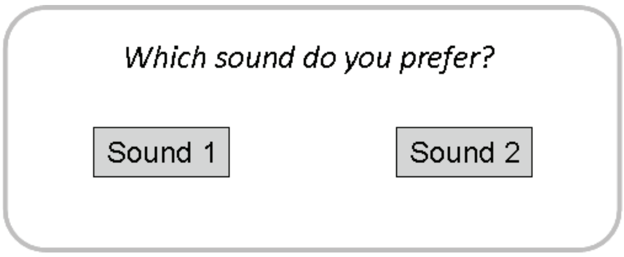


Figure 3.11: Participants have to choose the sound they prefere (an example here) before following the test with another pair.

An appropriate method is presented in 1998 [176]. The so-called *individual test* combines advantages of paired comparisons (direct comparison) and absolute judgment (direct estimation). Since, other authors have used this new approach, Chevret and Parizet [7] which called it a *mixed evaluation*. With this mixed procedure, all sounds are available to the participants and they choose one to listen to and evaluate. In order to validate the experiment on the car doors' closing sound (the example of Figure 3.12), they compare this methodology with a classical paired comparison. Results of these two studies are very similar with a much shorter experimental time for the mixed method (approximately 15 minutes for the paired comparison vs. 6 minutes for the mixed procedure).

For other sound quality applications in automotive, authors like Susini [37], Nosulenko [151] or still Parizet [27] have used this technique as a preliminary step for a preference evaluation.

I have used the paired comparison methodology twice during my work for MultiDimensional Scaling experiments. In both tests (acoustic one detailed in Chapter 6 and the vibroacoustic one in Chapter 8), 105

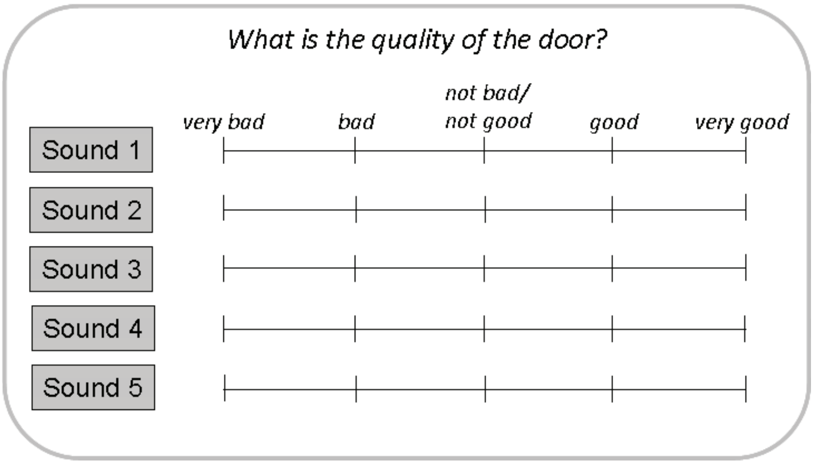


Figure 3.12: Question asked during the mixed evaluation experiment [7].

pairs were presented to participants. The first part was devoted to the assessment of the dissimilarity between sounds (on a continuous scale from "very similar" to "very dissimilar"). The second part was devoted to a preference assessment.

3.2.2.6 Discussion

As mentioned before, methodology's choice is important in accordance with the nature of expected results at the end of the experiment. But another question to resolve during the preliminary phase of any subjective work concerns the experiment's context. In the case of study which concerns us, the question was to know whether the different tests would be realized in a real situation with active participant driving or in laboratory context. As precised in Chapter 4, all experiments performed during this thesis took place in the laboratory. In contrary, others have chosen to carry out their experiments in real driving conditions. Indeed, during their thesis work, Barbier [64] and Astruc [186] chose to execute their experiments in running conditions. The first, works in which the behavior of customers during situation like acceleration (overtaking of other vehicles or insertion way on highways) is studied and the second, focuses on the methodologies' improvement for dynamic studies.

Several working groups have already been interested in comparing results between real and laboratory contexts. Indeed, Bézat [81] compares in 2006 these two kinds of situations. For each of the two contexts, 60 participants evaluate the engine noise. For those installed in non-real situation, a video was associated to stimuli. Results show that the real vehicle context has a stronger effect than the video. On the other hand, it seems that adding contextual factors in laboratory (image or video for instance) is not sufficient to approximate the real immersion effect. Genuit [187] presents an interesting comparison experiment more particularly in vibration study. Three scenarios were evaluated: *in situ* in vehicle, in simulator and in a laboratory. For the first two contexts (real vehicle and simulator), sound and vibrations were estimated, whereas in the laboratory, the acoustic modality is only presented to the participants. Results show a strong correlation between experiments despite a slight difference for the use of rating scale. Participants use a smaller dynamic range for the simulator than in the vehicle. Results are even closer between the first two scenarios. However, the author emphasizes that contextual differences (vibration or not) are a possible explanation for the dispersion observed between vehicle/simulator and laboratory. Also, a study realized by Ford on Diesel vehicles [66] leads to this conclusion: when a driver has no interaction with his car (e.g. at idle, constant speed, 2^{nd} gear full load), judgments in the laboratory and on the trails are similar. On another hand, when the driver requires a sound feedback for his driving manner (traffic light start for instance), results partly differ. Results in 2^{nd} gear full load are reassuring. They give confidence about the possibility to work on this driving situation in a laboratory. During this study, Heinrichs and Groemping focused on driver and co-driver positions and did not see significant differences in the real situation. In 2^{nd} gear full load, context has a weak influence. But, in partial load, the context is important. The reason mentioned concerns itself with the driver activity in this type of driving situation. Bodden [188] even gives advantages and drawbacks of the two kinds of situations. Indeed, advantages of laboratory tests are the reproducibility, the identical test conditions for all participants, a direct comparison and a time-efficiency test. In contrast, the field test shows other advantages: a representative situation for the use of a product in daily-life, a typical handling of the product or a direct interaction with the product.

This chapter presented a subjective approach of Diesel car by introducing perception's notion and subjectivity linked to it. Indeed, as we could see, noise (or sound) is produced either by a human intention or by a sound feedback of the product's functioning and causes reactions of the individuals. First, it can prove to be a functionality. Horn [41], whose function is to warn other drivers of potential hazard, delivers an explicit message of emergency [189] understood by all. Moreover, it can contribute to an implicit message with a rather commercial approach. Indeed, the product "has to" reflect a positive image and to facilitate its own purchase. Although we were not going into the sound design's stage in this work, it is important to remind that like for architectural design, sound design of engine or of door closing noise [80] [82] (in the automotive case) are significant parameters in the evaluation of quality, comfort, performance and even pleasure. It has become representative and safety of the product. The goal reached in this case relates to a safe image conveyed by the car. Concerning the "natural" sound feedback (referring to the feedback which is not a human consequence), the case of wrong noise emitted by the vehicle during functioning (*"there is noise in my car"*) has already been evoked.

In the car industry, human subjectivity is increasingly taken into account in the creation process of the "product". However, as this chapter could demonstrate, a lot of parameters have to be taken into account to describe and understand the subjectivity (influence of a modality on another one, experiment's methodology or participants' culture for instance). Therefore, it is difficult to realize subjective experiments. We always have to know the possible biases due to our choices. Moreover, with industrialization in the 19^{th} century the expression "sound nuisance" has become incontrovertible in French vocabulary. Thus, the "struggle" against noise and the establishment of standards (related to noise level) for sound quality was born. The possibility to process sounds thanks to technical analysis and synthesis has greatly contributed to the development of sound design.

PART II

EXPERIMENTAL PART

Chapter 4

Measurement methodology on vehicle

During this thesis work, several perceptual experiments were performed by participants and the following chapters will detail them (Chapters 5, 6, 7 and 8). As for all perceptual tests, several preliminary stages must be realized where the recordings and processing of stimuli represent the basis of all preparation for such experiments. Moreover, question of signals' reproduction setup is also covered during this preliminary work.

This chapter presents measurements realized in vehicles in order to collect all data (sound and vibration recordings). In the first part (paragraph 4.1), measurements and reproduction setup for acoustics data are introduced whereas in the second one (paragraph 4.2), I focus on vibrations in the same way as in the first part (through the recordings and the reproduction system).

During measurements, sounds and vibrations have been recorded in synchrony.

4.1 Acoustics recordings

A sound database was recorded. The first measurement campaign allowed to record different types of cars - Diesel, gasoline and even hybrid ones - of Renault and of other automotive companies. This work stage allowed me to familiarize with Diesel noise in particular (paragraph 4.1.1). Afterwards, when I used to hear different kinds of engines and when I was able to recognize Diesel cars from others with less difficulty, I could set about real measurements. All recordings have been used for the different perceptual experiments (paragraph 4.1.2).

4.1.1 First sound database

Like a musician who gets used to hearing his instrument and to recognize its timbre, the first step of this PhD work was to record different types of vehicles. This preliminary work can be reduced to a learning phase.

During this measurement's stage, several choices have been made:

- record different kinds of vehicles with different cylinder configurations (3, 4 or 6 cylinders) and of different car classifications[1];
- record several driving situations that all drivers can experiment in a daily-life trip,
- have an easy to use small, transportable measurement device.

Fourty seven different cars have been measured (Appendix C) in different driving situations (Table 4.1 p 56). The choice of vehicle was made arbitrarily. Indeed, I could obtain different cars according to their availabilities but the first goal was to have the possibility to record 3-, 4-, 5- and 6-cylinder cars with different motorizations.

Inside each vehicle recordings were performed with a small device from Head Acoustics named SQuadriga[2]. This system is easy to use thanks to its compact dimension, low weight and internal flash memory. Moreover,

Figure 4.1: Squadriga device (system with headset) by Head Acoustics.

measurements were made with a headset which combines microphones and headphones for recordings and listening. The global system is shown in Figure 4.1.

Each measurement has been made at a 48-kHz sampling frequency with 16 bit quantization.

4.1.2 Sound measurements on test tracks

After this first measurement campaign, other recordings were performed to prepare experiments. Also, the work was always made in the same way:

- record different kinds of vehicles with different cylinder configurations (3, 4 or 6 cylinders) and of different car classifications, on a same test track;
- record several driving situations that all drivers can experience in daily-life trips,
- use a dummy-head.

[1] Lower, Middle and Upper classifications.
[2] Its characteritics could be found in its datasheet at http://www.head-acoustics.de.

Stimuli corresponding to twelve various driving situations recorded in fourteen different cars (3, 4, and 6 cylinders, Diesel and gasoline ones). Table 4.1 and Table 4.2 p 58 present driving situations and vehicles' characteristics, respectively.

Those driving situations have been chosen for one main reason: to present to the participants driving

Stationary situations	**Unstationary situations**
Hot idle	Start up the motor
50-kph	Stop the motor
70-kph	Traffic light start
90-kph	Acceleration
110-kph	Deceleration
130-kph	Traffic jam

Table 4.1: Twelve various driving situations.

situations known and used by all in a daily-life. However, the main difficulty for recordings of the unsteady driving situations is the reproducibility, but it seemed unjustified to ask people to evaluate situations they did not know, never used and/or never heard (as 2^{nd} full load or 3^{rd} full load already seen in section 2.2.3). All recordings were performed on the same part of acoustics tracks of Renault. The six steady situations are the easiest to record and reproduce. The unsteady ones were made case by case. Indeed, *start up the motor* and *stop the motor* are really short, but the recordings simply consist of switching on the ignition and cutting off the engine. Moreover, *traffic light start* and *acceleration* are similar enough. Indeed, during the recordings, the gear shifts were made in precise moments. Figure 4.2 summarizes those changes (the cases A and B of the figure precise the gear changes for 5-speed and 6-speed cars, respectively). In addition, the *deceleration* consists of making the contrast of *traffic light start* and *acceleration* with downshifts in precise moments.
This is detailed in the case C of Figure 4.2. Finally, for *traffic jam*, the recordings consist of a succession of gear shifts and downshifts between the 2^{nd} and the 4^{th} ones.

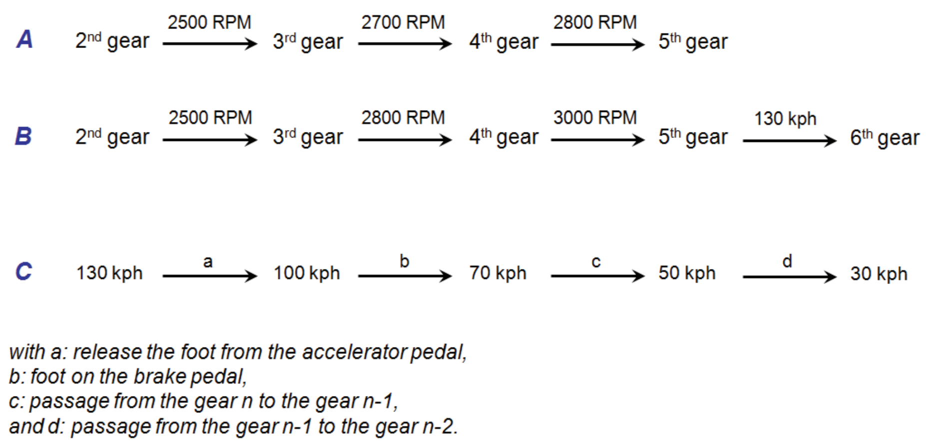


Figure 4.2: Gear changes during the recordings of *acceleration* (case A and B for respectively 5-speed cars and 6-speed ones) and of *deceleration* (case C). For instance, for a 5-speed car (case A), the different gear changes during a recording of *acceleration* were made like this: (i) at 2500 RPM, we go from the 2^{nd} gear to the 3^{rd} one (ii) at 2700 RPM, we go from the 3^{rd} to the 4^{th} one and (iii) at 2800 RPM, we go from the 4^{th} to the 5^{th} one. Concerning the *deceleration* case (case C), it was easier and more reproducible to make the recordings based on the speed rather than on the engine speed.

Moreover, the choice of cars was made according to two factors: the vehicle's interest and its availability. Indeed, the whole of vehicles have been kept for their acoustics features among vehicles of Appendix C. Hyundai Getz, Peugeot 308 and Renault Laguna Coupé (marked with * in Table 4.2 p 58) have been recorded for Dieselness tests (Chapters 5 and 7) in order to keep cars with different number of cylinders and from three various classifications. The seven other cars (** in Table 4.2) have been used to complete the database with several vehicles for each classification. And finally, the last ones (*** in Table 4.2) have been kept in order to represent new models of Renault's market with two different motorizations (gasoline and Diesel).

For measurements, the equipment used was a dummy head (HMS III of Head Acoustics) on the co-driver seat. This device, simple to use, allows to recreate the sound space effects during stimuli reproduction. It simulates as well as the influence of the body and head on the pressure field inside the car. Figure 4.3 illustrates

Figure 4.3: Dummy head placed at the co-driver position during sound measurements.

how measurements happened with the dummy-head at the co-driver position.

Each measurement was made at a 48-kHz sampling frequency with 16 bit quantization.

4.1.3 Sound reproduction in laboratory

4.1.3.1 Data processing

Different processes were applied to signals in order to prepare them for the perceptual test:

1. the data export from LMS format to wav format,
2. the resampling of data,
3. the segmenting of sound signal,
4. the application of fade-in and fade-out.

Indeed, the dummy head is linked to LMS device - which allows vibrations measurements - sound recordings were obtained in LMS format. An export is necessary in order to pass from the original format to the wav one.

A step of resampling to 44.100 kHz is done. The same quantification is kept (16-bit quantization).

During the third processing, time reduction of the recordings was done. Indeed, situations like *acceleration* or *traffic light start* can last 120s whereas situations like *start up the motor* or *stop the motor* last only 3s. Of course, we can not reduce *acceleration* or *deceleration* to 3s, and we can not extend the shorter ones. Therefore, we cut stimuli in different manners: for the steady ones, in a same experiment, their length is the same. Concerning the unsteady ones, all *start up the motor* and *stop the motor* last 2s. Differences exist especially for the others (*traffic light start*, *acceleration*, *deceleration* and *traffic jam*). Concerning *traffic jam*, recordings present speed changes (with acceleration and deceleration series) and gear shifts. The choice was to keep one gear's change with a length of 20s. For the three other situations (*traffic light start*, *acceleration* and *deceleration*), we based judgment on engine revolution and on the first gear shift (from the 2^{nd} to the 3^{rd} one). However, in accordance with the type of vehicle, we could not obtain exactly the same duration. Indeed, the main harmonic of a 4-cylinder car is the 2^{nd} one, whereas it is the 3^{rd} harmonic for a 6-cylinder vehicle (paragraph 2.2.2 in Chapter 2). Following the behavior of the proper harmonics from the beginning of recordings (from *hot idle* around 1000 RPM), stimuli obtained did not exceed about 20s.

Finally, in order to have clean data without artifacts (on which people could focus), we applied the same fade-in and fade-out to all recordings.

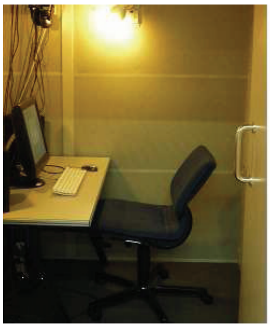
After those different treatments, the following paragraph presents the device used during the experiments.

Cars manufacturer	Vehicle model	Engine	Cylinders' geometry	Powerful	Gearbox	Car Classification
Hyundai	Getz *	Diesel	L3	82	5-speed manual	Lower
Hyundai	I10 **	Diesel	L3	75	5-speed manual	Lower
VW	Polo **	Diesel	L3	75	5-speed manual	Lower
Citroën	C5 **	Diesel	L4	110	5-speed manual	Middle
Fiat	500 **	Diesel	L4	75	5-speed manual	Lower
Mercedes	MC220 **	Diesel	L4	170	5-speed automatic	Upper
Peugeot	308 *	Diesel	L4	110	5-speed manual	Middle
Renault	Mégane ***	Diesel	L4	105	6-speed manual	Middle
Renault	Grand Scenic ***	Diesel	L4	105	6-speed manual	Middle
Renault	Mégane ***	Gasoline	L4	110	5-speed manual	Middle
Renault	Grand Scenic ***	Gasoline	L4	110	5-speed manual	Middle
Citroën	C6 **	Diesel	V6	211	6-speed automatic	Upper
Peugeot	407 Coupé **	Diesel	V6	204	6-speed automatic	Middle
Renault	Laguna Coupé *	Diesel	V6	235	6-speed automatic	Middle

Table 4.2: Fourteen different cars measured on test tracks.

4.1.3.2 Sound reproduction device

For all experiments, sound reproduction device was always the same. For each test and in each country, experiments took place in a soundproof booth (Figure 4.4) with the same playback system (HPS IV amplifier of Head Acoustics and a Sennheiser half-opened electrostatic headphone). Indeed, in order to keep this parameter fixed, the sound device was sent to different teams where experiments were performed.



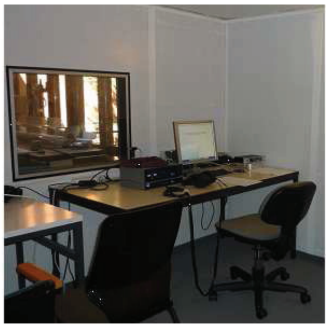


Figure 4.4: Example of two soundproof booths where some sound experiments took place: at IRCAM (left) and at Oldenburg University (right).

4.1.4 Vibrations recordings

4.1.4.1 Vibrations measurements on trails

Vibrations have been recorded in synchronization with the sounds on the test ring. The equipment used was Scadas SCM-05 of LMS3. Two three-axis accelerometers (PCB - ICP) were used: one located on the steering wheel's hoop and the other, on the left back side of the driver seat. Figure 4.5 presents the accelerometers' positions.

Accelerometers' positions do not comply with references of ISO 10326-1 [8]. Indeed, it defines a method allowing the measurement of the seat's vibrations (for back and seating). The standard specifies that vibrations' measurements should be done using an accelerometer placed at the seat's center, in a disc of 250 mm $+/-$ 50 mm diameter, as thin as possible (with a thickness which does not exceed 12 mm) in plastic or in rubber (Figure 4.6).

Moreover, this standard proposes an alternative solution. It recommends to put the accelerometer in the closest possible location of the contact zone between the participant and the vehicle. Choosing the left back point of the sliding seat as the reference was a good compromise. It overcame the effect of different seats on results' variability and it is close enough to the participant.

The two digital outputs of the dummy head and the three channels (x, y and z directions) of each accelerometer were linked to the eight inputs of the LMS Scadas device.

4.1.5 Vibrations reproduction in laboratory

4.1.5.1 Data processing

In the same manner as for the sound recordings, preparation of vibration data consisted of:

1. the data export from LMS format to wav format,
2. the resampling of data ,
3. the segmenting of sound signals,
4. the application of frequency filters,
5. the application of inverse transfer function (whose measure is explained in 4.1.5.3),

6. the application of fade in-and fade-out.

Figure 4.5: Locations of the three-axis accelerometers (blue) on the steering wheel (left side of the figure) and on the left back side for seat (right side of the figure) during vibrations' recordings.

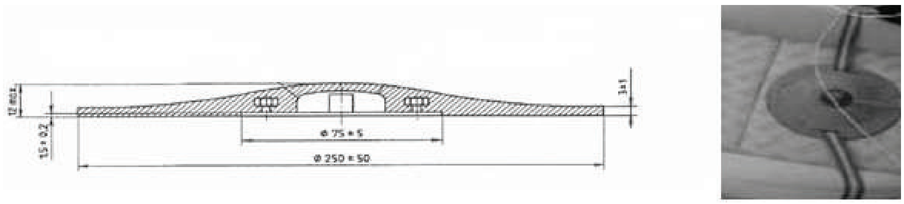


Figure 4.6: Dimensions and picture of the measurement device for the seat's vibrations defined by ISO 10326-1 [8].

For the processing 1., 2., 3., and 6., the treatments are the same as for the sound stimuli.

Two treatments steps were added for vibration preparation. First (step 4.), vibration signals were filtered from 20 Hz to 150 Hz for the seat and from 20 Hz to 300 Hz for the steering wheel. These choices were made for different reasons. We decided not to reproduce the accelerations below 20 Hz for two reasons. First, Figure 7.2 shows that - in the "worst" case for the 3-cylinder car which has the strongest vibration level - the accelerations are really weak and neglected below 20 Hz for the seat (at left) and for the steering wheel (at right). Secondly, below 20 Hz, physical disorders can appear (with resonances of stomach at 4-5 Hz, of liver at 4-8 Hz, of heart at 5-6 Hz and of kidney at 6-12 Hz) (Figure 3.6 in Chapter 3).

Finally, concerning the non-reproduction of the accelerations higher than 150 Hz, measurements of electrodynamic exciters show two resonances. A first and most important one around 15 Hz which corresponds to rigid body mode, and a second, weaker one around 150 Hz due to moving parts (Figure 7.3). Moreover, weighting curves (Figure 7.4) indicate that sensitivity reduces above 150 Hz (for seat).

By taking into account those three pieces of information, we limit the seat frequency range between 20 Hz and 150 Hz. Concerning the steering wheel, Barth [126] precised that it contributes strongly to the vibrations' perception especially beyond 100 Hz.

In addition, Figure 3.6 which highlights theoretical resonance frequencies of different body parts, shows a sensitivity in a frequency range of 50-200 Hz for hands. Also, Giacomin and Ajovalasit [65] conclude that vibration energy can reach frequencies of up to 300 Hz and vibration modes with large resonant peaks appear for frequencies from 20 to 50 Hz. Therefore, filtering was made from 20 Hz to 300 Hz for the steering wheel's signals.

To have a reproduction as faithful as possible, signals are filtered taking into account the bench behavior (step 5.) against vibrations' solicitations (cf 4.1.5.3).

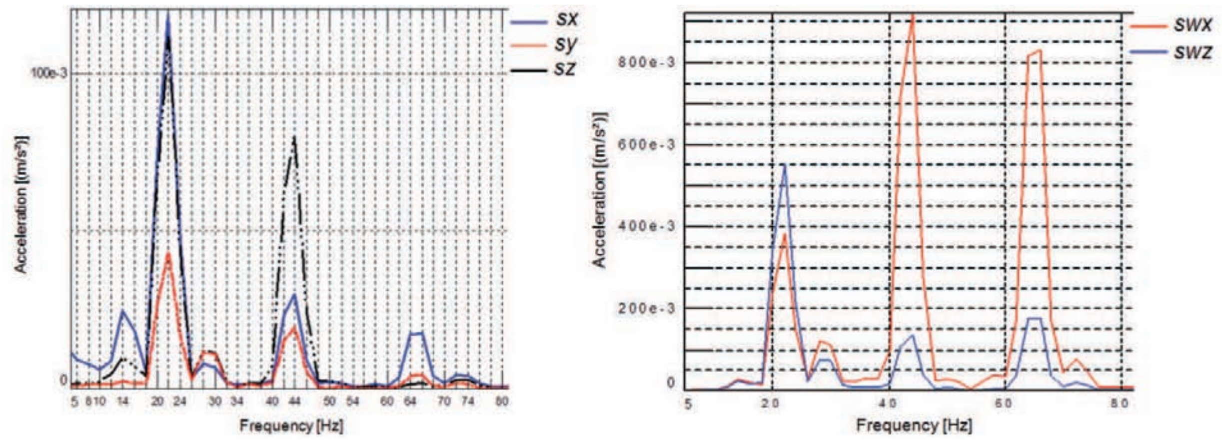


Figure 4.7: Frequency responses of the bench for a 3-cylinder car *hot idle* signal (Hyundai Getz). At left, the seat frequency response (x direction in blue, y in red and z in black) and at right, the steering wheel frequency response (x direction in red and z in blue).

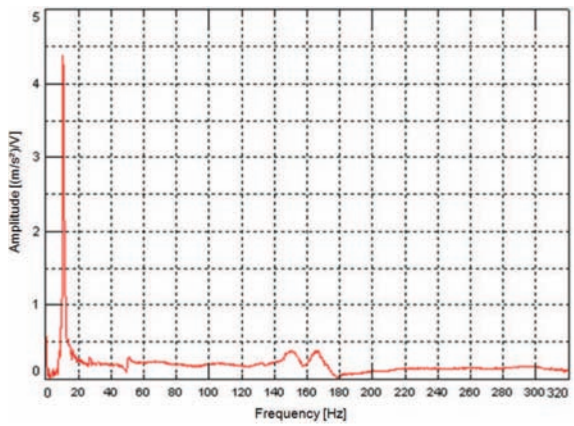


Figure 4.8: Transfer function of one electrodynamic exciter. Two resonances at 15Hz and around 150 Hz are significant on all electrodynamic exciters.

4.1.5.2 Bench presentation

A simulation bench, made up of two independant parts, is used during experiments with vibrations. Figure 4.10 shows those two parts with the plateform and the crossmember of the steering column. It is equipped with a car seat and a car steering wheel and reproduces vibrations of three directions (x, y and z) for the seat and those of two directions for steering wheel (x and z in France and y and z in Germany[3]). For this, twelve electrodynamic exciters reproduced the vibrations of the platform (four for each direction) and two others for the vibrations' reproduction of the steering wheel (one per direction). Those electrodynamic exciters allowed to generate broadband frequency vibrations within the framework of automotive studies. Figure 4.10 presents the French bench with the fourteen electrodynamic exciters' positions (in yellow).

The wooden platform with a rigid seat rests on the ground with a rectangular frame in aluminum. Electrodynamic exciters used on the bench consist of a motor similar to a loudspeaker's. The small difference is that the magnet moves and not the coil. The magnet is held in the magnetic field induced by the coil using

[3] Indeed, benches developed by ITAP GmbH (http://www.itap.de) are not totally similar. Structure are really close (even if French one is less heavy than German one because it is more recent and because some improvements have been done) but seat and steering wheel are different. For German bench, seat and steering wheel come from VW Golf whereas for French one, they come from Renault Mégane. Moreover, axes of steering wheel differ with y and z for German one and x and z for French one. This difference is independant of my control. However, I just precise that measurements show that the most dominant and strongest directions at the steering wheel are x and z.

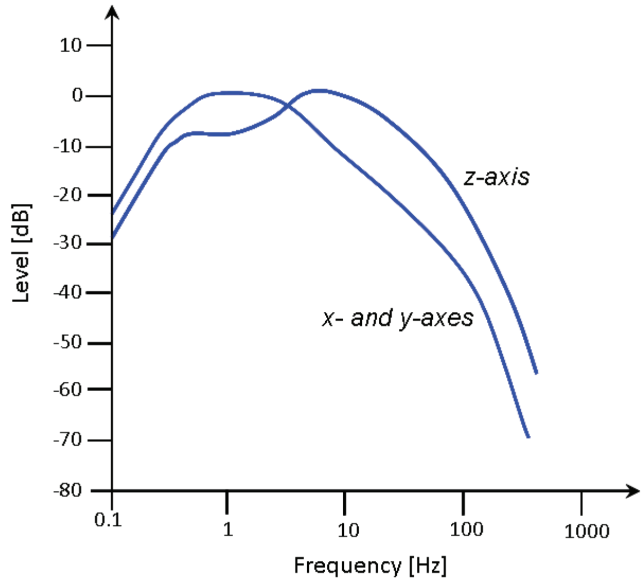


Figure 4.9: Weighting curves for seat sensitivity [9].

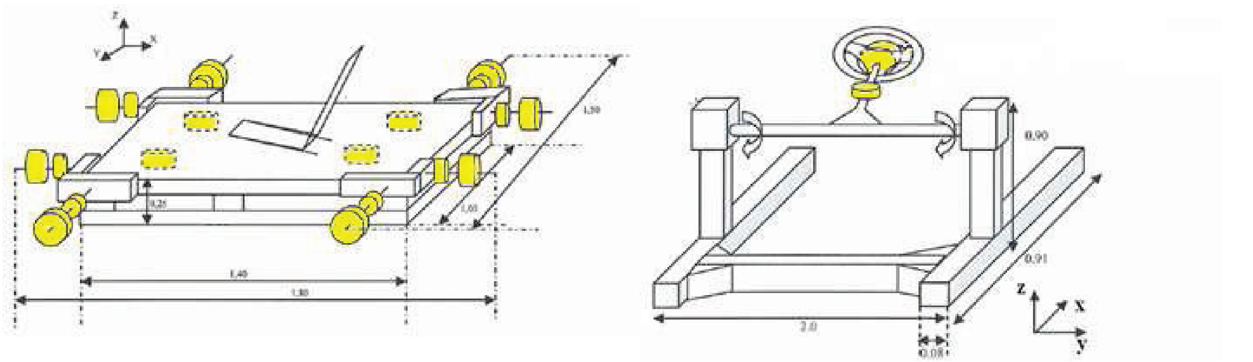


Figure 4.10: French bench: Schematic representation of the platform (left side) and of the steering column cross member (right side) with the fourteen electrodynamic exciters' in yellow.

two suspensions in resin. Electrodynamic exciters have an additional mass of 2.5 kg. For each one, movement of this mass allows the bench to vibrate.

4.1.5.3 Bench preparation

Bench measurements

Signals reproduced by the bench have to be the same as those recorded in vehicle. For this, we have to minimize the influence of the bench. Therefore, signals are filtered taking into account the bench's behavior. For this, measurements consist of several stages:

1. measurement of bench's frequency response to a white noise (for each of five directions: three for seat and two for steering wheel);
2. calculation of the inverse frequency response,
3. validation of the flat frequency response of the bench.

Initially, transfer function between the electrical signal from the amplifier and the acceleration from the accelerometer (Figure 4.5) is recorded (for all directions, one by one). This transfer function is defined by the following equation and Figure 4.11 shows a synoptic diagram of this measurement:

$$Y(z) = X(z) * H(z) \Leftrightarrow H(z) = \frac{Y(z)}{X(z)} \tag{4.1}$$

Then, in order to allow a response to be as flat as possible from the bench, the measured transfer functions

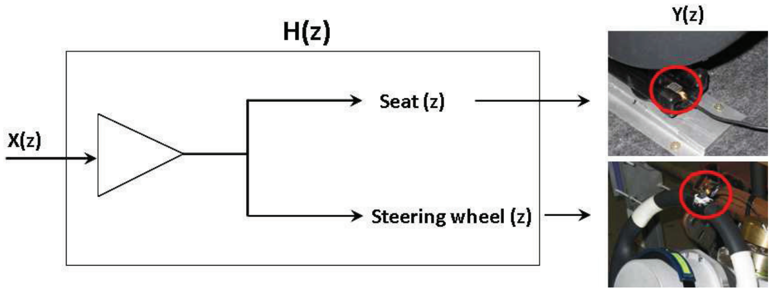


Figure 4.11: Synoptic diagram of measurements with picture of three-axis accelerometer on the left back side for the seat (top) and on the steering wheel's hoop (bottom).

have to be filtered with their inverse. To check effectiveness of filter, two stages have been validated. First, we use white noise filtered by transfer function's inverse and check the frequency response of the bench that gave a flat response. Secondly, we do the same validation with recordings of vehicles (steady ones), filtered in the same way. Besides, Figure 4.12 shows the frequency response of the bench with a white noise (green curve) and with the same white noise filtered by the transfer function's inverse (red curve). We can see that in the red case, the frequency response is flatter.

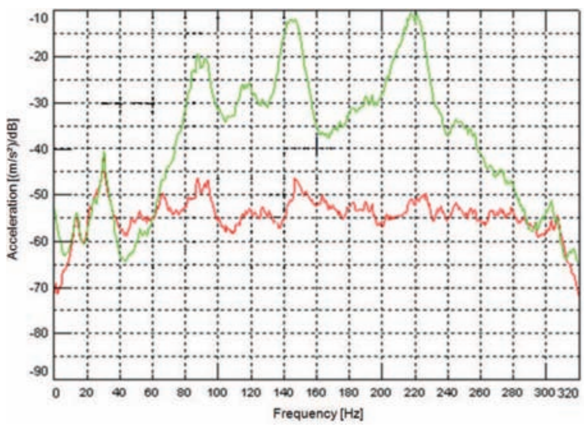


Figure 4.12: Frequency response of the bench with a white noise (green curve) and with the same white noise filtered by the transfer function's inverse (red curve).

Moreover, Figure 4.13 presents the cross effects measures of the platform : (a) the vibrational levels measured in the three directions when the x direction is excited by the white noise; (b) the vibrational levels measured in the three directions when the y direction is excited by the white noise and (c) the vibrational levels measured in the three directions when the z direction is excited by the white noise. Therefore, by looking at case (a), we notice that the vibrational levels measured in the direction, which is not excited by the white noise, are negligible compared to those measured in the excited direction even if some sensitive areas exist. Indeed, below 40 Hz two common modes exist between the directions x and y with similar levels. Also, between 140 Hz and 160 Hz, the measured levels of the z direction are higher. The assessment is the same for case (b) and (c) where y and z directions are excited, respectively. However, despite these remarks, it was revealed to be difficult to take into account the global transfer matrix, and we have decided to neglect the cross-terms' influence. The approximation can be done because the levels are lower enough compared to the levels of the excited direction.

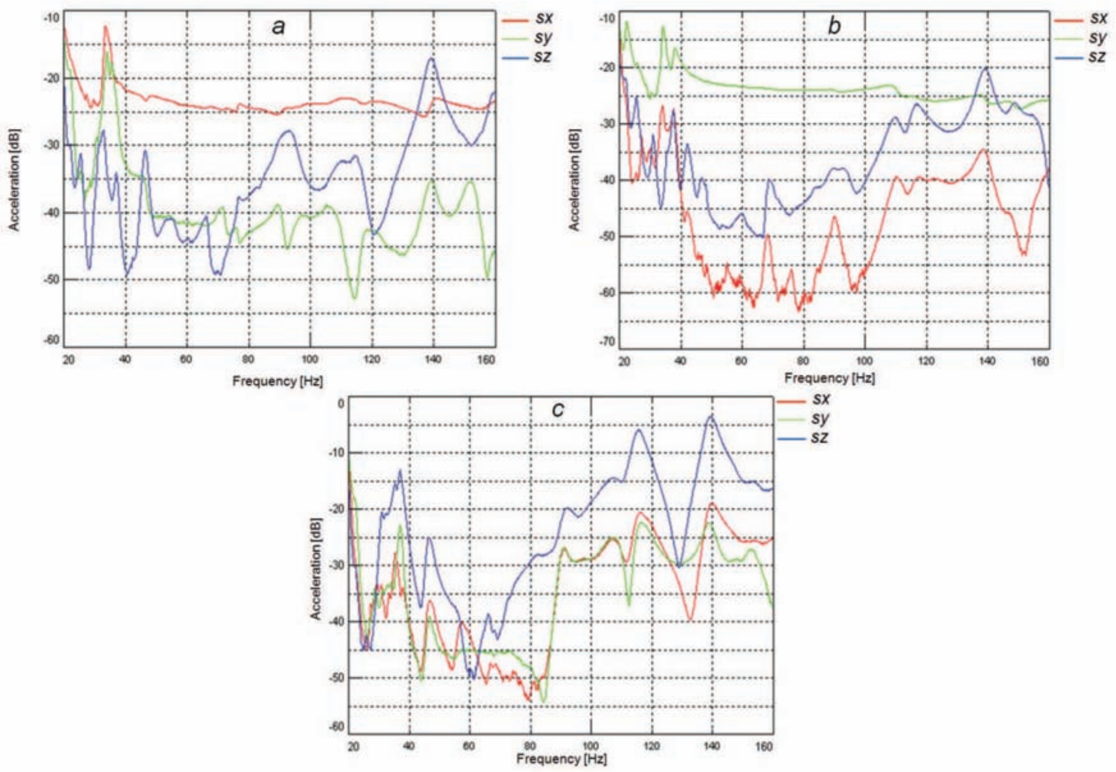


Figure 4.13: Cross effect of the platform : (a) vibrational levels measured in the three directions when the x direction is excited by the white noise; (b) vibrational levels measured in the three directions when the y direction is excited by the white noise and (c) the vibrational levels measured in the three directions when the z direction is excited by the white noise.

Finally, in order to reproduce signals during experiments, a seven channel wav file was created with sound stereo files and five vibrations' recordings. Each new wave file is made at a 44.100 kHz sampling frequency with 16 bit quantization.

Vibrations reproduction setup

In order to reproduce in synchronization sounds and vibrations, Figure 4.14 presents the setup for the restitution.

Indeed, the whole system was driven by a computer equipped with MaxMSP system[4]. A multi-channel sound card (Sound card RME Fireface 400) linked to the computer, presented the vibration signals to amplifiers (Yamaha P7000S) and acoustic ones to headphones (paragraph 4.1.3.2). All amplifiers supplied the fourteen electrodynamic exciters of the bench.

During all tests, each participant was left alone in the soundproof booth. They were totally self-sufficient. The computer screen was put in front of them. A woodcut was manufactured in order to provide a comfortable use of the computer's mouse (at their right side). Let's precise here that the reproduction of vehicles' vibrations do not totally correspond to those in real cars because the seat effect is not taken into account.

[4] MaxMSP is a software developed at IRCAM in the 1980s. It allows to make sound synthesis, recording and MIDI instruments' control. It is one of the most used music software by professional musicians [190] (http://forumnet.ircam.fr/237.html).

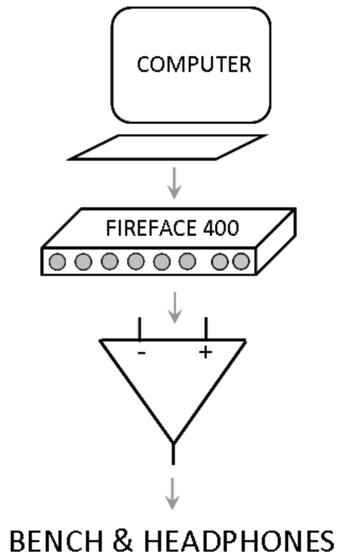


Figure 4.14: Reproduction setup for sounds and vibrations from computer (at the top) which generates seven channels .wav files. Each file goes through Sound Card (RME Fireface 400) and amplifiers (one per direction) before arriving to the headphones and the bench.

Thanks to this chapter, all recordings and processings of stimuli (acoustics and vibrations) have been exposed. The following table sums up the different treatments realized:

Acoustics signals	**Vibrations signals**
1. export signals from LMS to wav format	1. export signals from LMS to wav format
2. resampling from 102.400 kHz to 44.100 kHz	2. resampling from 4.096 kHz to 44.100 kHz
3. segmenting data	3. segmenting data
4. fade-in + fade-out	4. frequency filter (20 Hz-150 Hz for seat and 20 Hz-300 Hz for steering wheel)
-	5. application of the bench's inverse transfer function
-	6. fade-in + fade-out

Table 4.3: Different steps of processings for acoustics and vibrations signals.

The sound and vibration recordings can be reproduced as faithful as possible to the reality despite some simplifications thanks to the bench. It does not represent a real vehicle but allows participants to place them in a realistic environment.

STEP I

SOUND PERCEPTION OF DIESEL

Chapter 5

Sound perception of Dieselness

As detailed in Chapter 3, the Diesel vehicle is one of many daily-life sound sources that each person may qualify according to his or her sensitivity. However, everybody remembers their own Diesel noise with their own definition and feelings. In order to succeed in describing this particular sound, we must, above all, know *what* best represents Diesel noise by focusing on *when* people recognize this Diesel sound. For this a psychoacoustic experiment was realized with various steady and unsteady driving situations[1] in order to identify which one(s) best represent(s) the characteristic sound of a Diesel vehicle.

This chapter presents the experiments carried out to answer an important question of this thesis: which driving situation(s) allow us to realize that we are driving a Diesel vehicle? It describes the detail of the experiment realized in France and in Germany, which allows us to extract the "object" (the driving situations) on which afterwards we will work. The first part is devoted to the experiment and its results (5.2) before tackling this topic across an intercultural approach in the second part (5.3).

[1] J-C Kraemer [58] precised that *"We can understand that functioning noise of a vehicle depends on the conditions of use and that they can not be described by a single value or even a single spectrum. Idle, low speed on gravel road, acceleration, high constant speed on highway, are as much as situations for which, dominant noises have different levels and different origins. Conditions of use* (that we have already tackled in section 2.2.3 in Chapter 2) *impact not only noise level, but also relative importance of different sources and spectral composition of overall noise".*

5.1 Dieselness definition

Dieselness is a specific characteristic of the sound generated by the internal combustions of the Diesel fuel in the combustion chambers of the cylinders of a Diesel engine. The Dieselness characteristic is the impulsive character of the Diesel sound often referred to as "Diesel knocking". According to the different paths of sound propagation, the perceived Dieselness of the same engine may differ depending on whether the engine sound is heard in the interior of a car or outside. In the context of the study the Dieselness may vary according to the more or less impulsive character of a Diesel engine sound.

The following experiment allows us to know *which* driving situation (among twelve different) best characterizes Dieselness. By using the *Dieselness* term, I want to refer to "Diesel character", which stimuli remind participants of their experience with a Diesel car.

Contrary to the approach of Fastl et al. [20], I did not give an exact definition of Dieselness to participants. Only, the experiment's instruction (Appendix D) gave some details about it, e.g. *"Up to what point does this stimulus corresponds to a typical driving situation of a Diesel car? In other words, up to what point does it call up a Diesel stimulus? Up to what point does it allow you to be aware of a Diesel car?"*. Finally, I let participants keep their own definition of Diesel character[2].

5.2 Diesel driving situations: the French listening test

This section presents the study in which we have identified the driving situations where actually the typical Diesel sound develops its proper characteristics, the Dieselness. Participants assess the Dieselness of sounds that were recorded in different Diesel cars in different driving situations. Thirty-six stimuli are presented to the participants (twelve driving situations and three vehicles). Each sound stimulus is repeated once in order to be able to check the reliability of the participants' answers. For each sound presented participants make their Dieselness judgment on a continuous scale taking into account the entire stimulus.

This experiment was carried out in France and Germany to check for possible cross-cultural differences. This section describes the test and results for the French participants.

5.2.1 Participants

Thirty French participants performed this listening test. For the recruitment participants had to meet some criteria. They must have not work in automobile or acoustic domains, to be a Diesel owner and use it regularly (daily or several times per week) and to be devoid of hearing problems (self report). Table 5.1 summarizes the information about the participants.

Men	**Female**	**Age [yo]**
13	17	43 (11)

Table 5.1: Data about French participants: number of men, of female, the mean age and standard deviation in brackets.

5.2.2 Stimuli

Stimuli correspond to twelve various driving situations recorded in three different Diesel cars (3, 4 and 6 cylinders from Lower to Upper classification). Table 4.1 p 56 and Table 4.2 p 58 present the situations[3] and the vehicles[4] assessed during the experiment. All of these situations can be encountered during a daily trip.

The recording protocol was already detailed in Chapter 4. No treatment was applied to the stimuli.

[2] In the following, I will use "Dieselness" or "Diesel character" terms to express the same idea.

[3] The twelve situations of Table 4.1 are proposed in this experiment.

[4] The three evaluated cars in this test are: Hyundai Getz (3 cylinders), Peugeot 308 (4 cylinders) and Renault Laguna Coupé (6 cylinders).

5.2.3 Apparatus

The experiment was performed in an IAC soundproof booth at IRCAM. The sound signals were reproduced with a Sennheiser half-opened electrostatic headphone and a HPS IV amplifier system of Head Acoustics (cf Chapter 4). No subwoofer was used to reproduce the low frequency.

5.2.4 Protocol

The test is made up of two parts with the same task to carry out. Indeed, each part corresponds to an evaluation of one Diesel car and its twelve driving situations. Therefore, each participant appraises two different vehicles. For the reliability of results, vehicles and driving situations are presented according to six different combinations: 3 cylinders/4 cylinders, 4/3, 3/6, 6/3, 4/6 and 6/4. Thanks to this protocol, five people evaluated each configuration; twenty, each vehicle and ten, for the same presentation's order. For instance, 3-cylinder car was evaluated in combinations 3/4, 4/3, 3/6 and 6/3. Ten participants assessed it when it was in the first part of the experiment (3/4 and 3/6) and ten others during the second part (4/3 and 6/3). The protocol's choice (with two vehicles per person) was made in order to minimize the duration of the experiment. With three vehicles per person, the test would have been too long.

Each part is made up of three stages:

- **orientation stage**: this stage allows participants to listen to a sound sequence made up of the twelve driving situations and even a bit more, in order to create a real fluent scenario of driving. The sequence consists of: *start up the motor*, *hot idle*, *traffic light start*, *70-kph*, *acceleration*, *110-kph*, *deceleration*, *traffic jam*, *130-kph*, *deceleration*, *90-kph*, *deceleration*, *50-kph*, *hot idle* and *stop the motor*. It lasts around 5 minutes;
- **identification stage**: in this stage, participants listen to each driving situation one by one in random order. They can listen to them as many times as they want. Twelve road signs (from highway code) or labels (as for *start up the motor* and *stop the motor* for instance) are proposed to participants. They have to choose for each stimulus the road sign which best corresponds to the event that they have just heard. Table 5.2 presents correspondence between situations and road signs[5]. During this stage, we offer participants the possibility to choose a thirteenth label ("the sound does not correspond to any road sign") if they do not succeed in finding an appropriate road sign among the twelve of Table 5.2.

Steady situation	Road sign	Unsteady situation	Road sign
hot idle		start up	START UP THE MOTOR
50-kph		stop	STOP THE MOTOR
70-kph		traffic light start	
90-kph		acceleration	
110-kph		deceleration	
130-kph		traffic jam	

Table 5.2: Twelve driving situations with their corresponding road signs or labels. Labels for *start up the motor* and *stop the motor* were translated in French and in German.

[5] Correspondence between situations and road signs has been checked beforehand with highway code and validated with some colleagues for their good understanding. We made sure that everyone understood meaning of each road sign.

- **evaluation stage**: the third stage consists of listening to driving situations and evaluating them on a Diesel continuous scale from 0 to 1 using a cursor. A short definition of Dieselness is given in the instruction as I have already mentioned in paragraph 5.1. 0 corresponds to a score given by the participant if he or she thinks that the stimulus does not evoke a Diesel engine sound at all. *A contrario* participant gives 1 when he thinks that the stimulus evokes a Diesel engine sound perfectly (Figure 5.1). In order to check participants' reliability, each of them evaluates each stimulus twice.

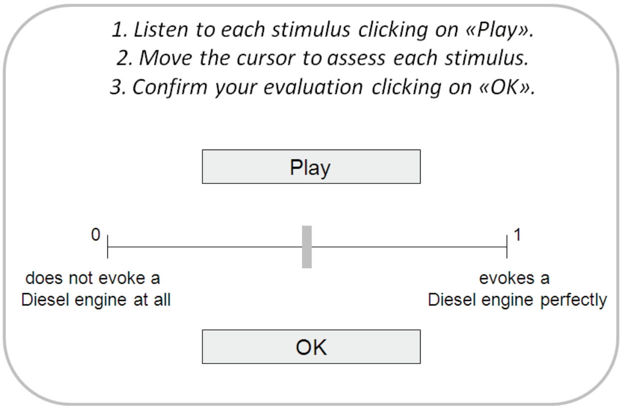


Figure 5.1: Direct Dieselness evaluation on a continuous scale from 0 (*does not evoke a Diesel engine at all*) to 1 (*evokes a Diesel engine perfectly*). Play the stimulus at the top, assess it in the middle and validate the choice with "OK" at the bottom.

To sum up the test stages, let's detail an example with a participant who assesses combination 6/3. First, he listens to the sound sequence of driving situations recorded in the 6-cylinder car (**orientation stage**). Then, he listens again to each stimulus one by one and chooses one road sign for each stimulus (**identification stage**). Finally, all stimuli are listened to twice (in a random order) and he evaluates each one on the Diesel continuous scale (**evaluation stage**). Then, the second part follows with the 3-cylinder car. Orientation, identification and evaluation stages happen in the same way.

Before starting the experiment an instruction was given to participants in order to explain the aim and the task of the experiment (Appendix D) for the instruction translated in French and in German). Moreover, when they finished the experiment, an interview was carried out with each of them in order to collect some personal information (age, brand and model of their car for instance) and their impression about the experiment. The test lasted around 48 min.

5.2.5 Results and discussion

5.2.5.1 Identification stage: the road sign choice

Twelve road signs

In this section, results of the **identification stage** for all thirty participants are presented. Figure 5.2 presents the percentage of participants who made the "right choice"[6] of road sign during this second stage. Correct recognition for each driving situation and for each vehicle percentage is presented. C1 in black round represents the 3-cylinder car (Hyundai Getz), C2 in red triangle, the 4-cylinder car (Peugeot 308) and C3, in green cross, the 6-cylinder car (Renault Laguna Coupé).

For all vehicles the best two recognizable driving situations are *start up the motor* and *stop the motor* with respectively 85% and 90% of recognition for C1, 100% for the two driving situations for C2 and 95% and 100% for C3. Secondly, for all *deceleration* and *hot idle*, recognition of road signs seems to be easier than for all other situations. Indeed, those two situations obtain respectively 55% and 70% of recognition for C1, 70% and 80% for C2 and 65% and 70% for C3. An explanation can be given for those four situations: *start up the motor*, *stop the motor*, *deceleration* and *hot idle*. As we can see in Table 5.2, *start up the motor* and *stop*

[6] I name "right choice", the choice made by the participant in the same way as the correspondence between driving situations and road signs of Table 5.2. This designation is no way a value-judgment and does not suggest the success of the experiment.

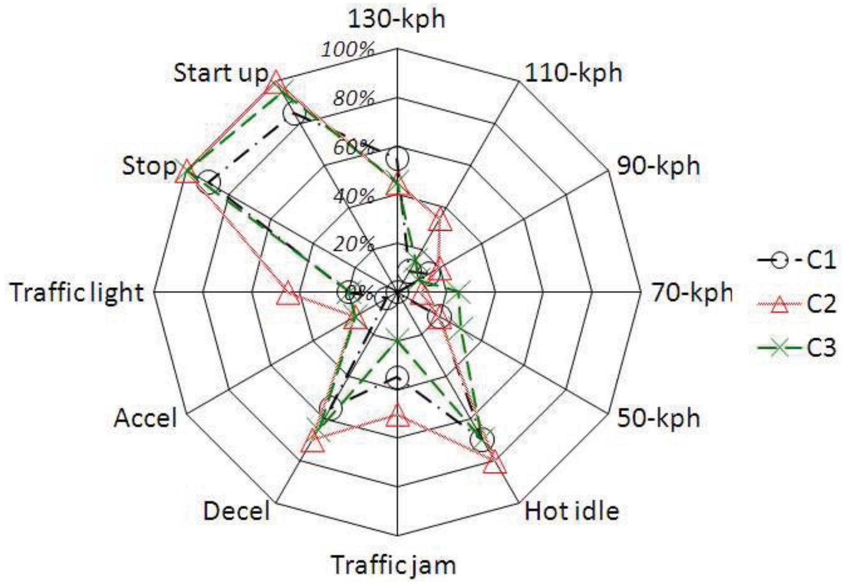


Figure 5.2: Percentage of French participants who chose the "right" road sign during the **identification stage**.

the motor have explicit labels. So, the significance of those two labels are easily understandable. This may explain (in addition to the particularity of their short duration of only 2s) that those two driving situations are really specific, thus, more recognizable. Concerning *deceleration* and *hot idle*, there are also meanings explicitly written on them ("stop 150 m" for the first one and "stop" for the second one). The identification task could be easier for these four road signs.

Among the six unsteady situations (*start up the motor*, *stop the motor*, *traffic light start*, *acceleration*, *deceleration* and *traffic jam*), *start up the motor*, *stop the motor* and *deceleration* are the most recognizable situations for all vehicles. The one which obtains the most "errors" is *acceleration* with 5%, 20% and 20% for C1, C2 and C3, respectively. Also, for all of the driving situations, participants have still easier found the correct road sign for C2 than for others. However, for *traffic light start*, *acceleration* and *traffic jam*, the methodology used can explain the difficulty of their recognition. Indeed, *traffic light start* and *acceleration* are situations whose spectrograms are really similar (Figure 5.3 gives the example for 3-cylinder car C1). Indeed, these two driving situations represent an *acceleration* more or less "pushed". *Traffic light start* imitates a progressive starting[7] when the traffic light becomes green. On the other hand, *acceleration* represents a strong acceleration as when one enters on a highway [64]. Spectrograms of Figure 5.3 show the emergence of the harmonics 3 (black line) and 4.5 (white line) in the same range of frequencies for the two driving situations. Moreover, let's precise that each one is recorded with two gear changes (the arrows on spectrograms). Finally, the percentage of road sign recognition for those unsteady situations follows the same tendency, whatever the car. The correlation coefficient between the recognition percentages for a comparison of vehicles two by two is high: 0.99 between C1 and C2, 0.95 between C2 and C3 and 0.96 between C1 and C3.

For the six steady ones (*hot idle*, *50-kph*, *70-kph*, *90-kph*, *110-kph* and *130-kph*) the case of *hot idle* is a particular case, and it has already been mentioned above. *130-kph* is the second one which obtains good recognition results with 55% for C1 and 45% for C2 and for C3. Therefore, they are the two most extreme steady situations which are well recognized. Of course we can understand by hearing the different stationary stimuli that it is difficult to discriminate between the *50-kph* to the *70-kph* to the *90-kph* to the *110-kph*. And this is confirmed with the verbalizations given at the end of the experiment during the interview: *"it is difficult to choose between the 90, 110 and 130 road signs"*, *"the part of road sign recognition is difficult"*, *"it is not obvious to find the right road sign for some sounds"*. In the same way as for the unsteady situations, the calculation of correlation coefficient gives 0.91 between C1 and C2, 0.85 between C2 and C3 and 0.90 between C1 and C3.

Finally, Table 5.3 presents the percentage of road sign recognition for the unsteady situations (at left)

[7] Named "takeoff" by people of automotive industries.

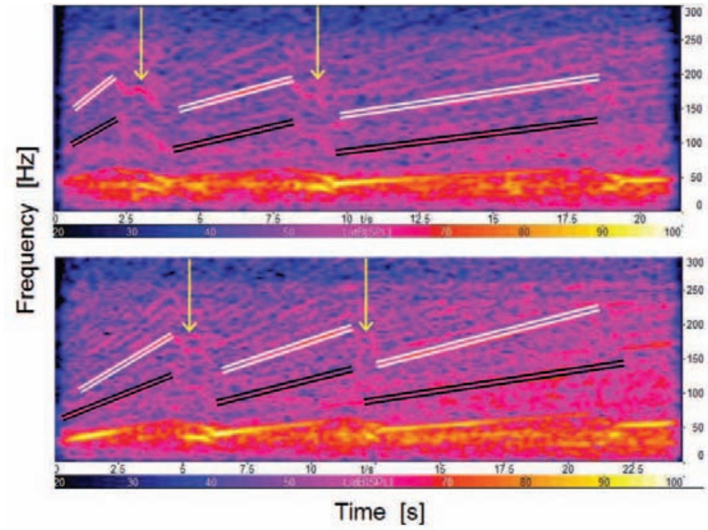


Figure 5.3: Spectrograms of the *traffic light start* (at the top) and of the *acceleration* (at the bottom) for C1. Emergence of harmonics 3 and 4.5 are presented in black and white, respectively.

and for the steady ones (at right) for the three Diesel cars C1, C2 and C3.

Cars	**Unsteady situations [%]**	**Steady situations [%]**
C1	48	28
C2	64	35
C3	53	33

Table 5.3: Percentage of road sign recognition for the six unsteady and the six steady driving situations for French participants during the **identification stage**.

The grouping of the unsteady situations on the one hand and of the steady ones on the other hand show that the unsteady situations are easily recognizable.

The thirteenth label

This **identification stage** has proposed to choose one road sign for each driving situation. Twelve situations had to be identified but a thirteenth label was proposed. Figure 5.4 presents it. In the same manner

Figure 5.4: The thirteen label proposed during the **identification stage**. It was translated in French and in German.

as for the twelve other driving situations, the proportion of participants who chose this label is presented in Figure 5.5.

None of participants used this thirteenth label for *stop the motor* (and this, for all vehicles). This comment is still true for some other situations like *start up the motor*, *acceleration*, *deceleration* and *hot idle*, but only for two cars each time (and not the same ones). However, we can not conclude that if participants did not choose this thirteen label, they have chosen the “right” road sign (this is especially true for *acceleration*, according to the weak percentage of participants who chose the “right” road sign in Figure 5.2). Moreover, we notice that it

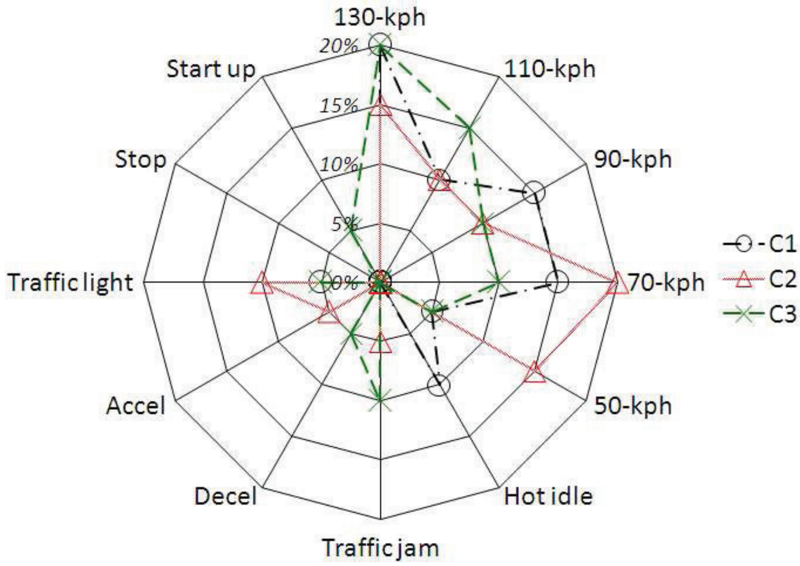


Figure 5.5: Percentage of French participants who chose the label "the sound does not correspond to any road sign" during the **identification stage**.

was chosen more for stationary situations than for unsteady ones. This highlights the difficulty of discriminating the different steady speeds.

5.2.5.2 Evaluation stage: Dieselness evaluation

Preliminary analyses

To reduce the number of parameters involved in the test (***P***, ***C***, ***V*** and ***S*** in Figure 5.6), preliminary statistical analyses was performed using the calculation of Pearson coefficient and an ANOVA analysis. This allows us to verify the robustness of results and to average Dieselness evaluations when statistical hypotheses are confirmed. Figure 5.6 presents steps to reduce the 4-dimension matrix M. ***P*** for participants of the experiment, ***C*** for combination of test (3/4, 4/3 or 3/6 for instance), ***V*** for vehicle (three different vehicles in this test) and ***S*** for driving situation assessed (twelve different situations). The two statistical processing methods allow us to obtain a reduced 2-dimension matrix which shows scores of each driving situation and each vehicle. This allows us to conclude on the driving situation(s) which best represent Diesel noise.

The calculation of the Pearson coefficient is made in order to examine the repetition factor. This coefficient allows us to know that 12, 7 and 14 participants are reliable in their evaluation of C1, C2 and C3, respectively. The participants obtain a correlation coefficient from 0.74 to 0.98 (for those who assessed C1), from 0.76 to 0.98 (for those who assessed C2) and from 0.72 to 0.96 (for those who assessed C3).

A repeated-measure analysis of variance (ANOVA) with three within-subject factors (2 Combinations' order[8], 3 Vehicles and 12 driving Situations) was performed. Therefore, we obtain three different analyses: one for combinations between C1 and C2, another one for combinations between C2 and C3 and one between C1 and C3. Results are presented in Table 8.6 to Table 8.8 in Appendix E. The first interesting result, which allows us to reduce data, concerns the influence of the combination's order (1^{st} line of each table). Indeed, they show that this factor has no effect on Dieselness appraisal. Moreover, the different interactions with this combination factor (V x C and S x C) do not prove any influence either. So, the Dieselness appraisals for each car can be averaged since the combinations' order has no influence on the assessments.

Dieselness results

The participants are asked to assess Diesel character of twelve driving situations (presented twice in a random order) on a continuous scale from 0 (*does not evoke a Diesel engine at all*) to 1 (*evokes a Diesel engine*

[8] 3/4 and 4/3 for instance.

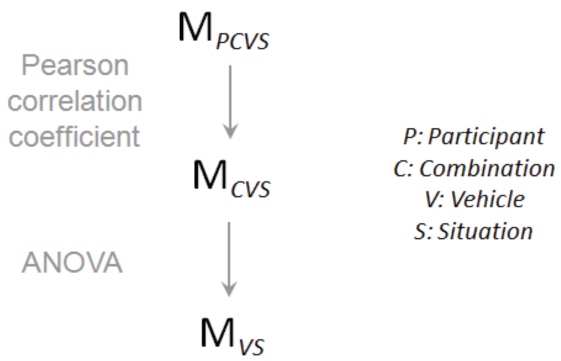


Figure 5.6: Reduction of 4-dimensions matrix with the Pearson coefficient and the ANOVA analysis.

perfectly). Figure 5.7 presents mean scores and standard deviations of those situations for the three vehicles (3-cylinder car C1 with black round, 4-cylinder car C2 with red triangle and 6-cylinder car C3 with green cross). Twelve driving situations given on the abscissa are divided into two parts: unsteady situations from *start up the motor* to *traffic jam* and steady ones from *hot idle* to *130-kph*.

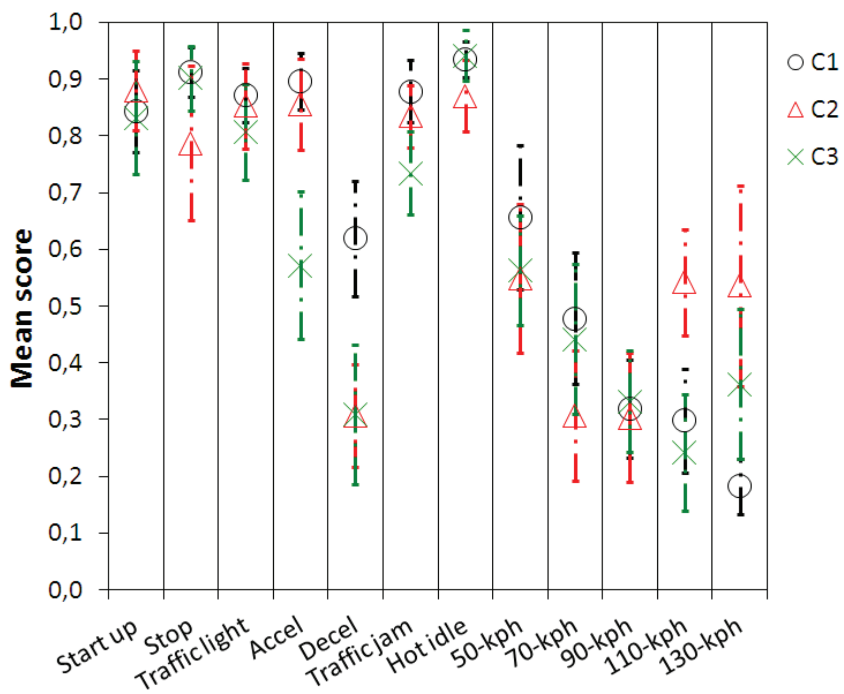


Figure 5.7: French participants: Dieselness mean scores and standard deviations of twelve driving situations for C1 (black round), C2 (red triangle) and C3 (green cross).

Influence of the vehicle

Figure 5.7 shows that the difference between vehicles is not so obvious for some cases. Indeed, we can see that mean scores of *hot idle* for C1 and C3 are very close (0.94 for C1 and 0.95 for C3) for instance. Moreover, the variance analysis confirms this with no significant influence of this factor on Dieselness appraisal (3^{rd} line of each table). Therefore, the vehicle has no impact on Dieselness evaluation.

Influence of the driving situation

Concerning the driving situation, we notice that scores are totally different according to the driving situation with a good use of Dieselness scale from 0.18 to 0.94. Also, the influence of this factor is confirmed by the variance analysis with $F(11, 88) = 12.5$, $p < 0.01$ for C1/C2; $F(11, 88) = 10.5$, $p < 0.01$ for C2/C3 and $F(11, 88) = 16.8$, $p < 0.01$ for C1/C3, respectively. Results show this factor's influence as the strongest effect among all factors and all interactions tested. According to the type of driving situation listened, Diesel character appears to be perceived differently.

Influence of their interaction (vehicle x driving situation)

By considering mean scores obtained for each vehicle (Figure 5.7), we notice that the first three driving situations which best represent Diesel engine (i) for C1 are *hot idle* (0.94), *stop the motor* (0.91) and *acceleration* and *traffic jam* (0.88) *ex-aequo* (ii) for C2, *hot idle* (0.88), *acceleration* (0.84) and *start up the motor* (0.83) and (iii) for C3, *hot idle* (0.95), *stop the motor* (0.91) and *start up the motor* (0.84). This remark is confirmed by the variance analysis which highlights the influence of the interaction between vehicle and driving situation about Dieselness appraisal with $F(11, 88) = 2.3$, $p < 0.01$, $F(11, 88) = 5.1$, $p < 0.01$ and $F(11, 88) = 2.9$, $p < 0.01$ for C1/C2, C2/C3 and C1/C3. The vehicle's influence on Dieselness assessment depends on the driving situation.

However, in the three cases (i), (ii) and (iii) *hot idle* appears to be the situation which best represents Dieselness and this confirms the reseachers and engineers' interest for this situation [19] [20] [26] [27] [33] [46] [65] [68] [126]. Indeed, all other situations obtain lower scores (especially the other steady ones and *deceleration* which appears to be an exception among the unsteady situations and confirmed by a contrast analysis). This can be explained by the fact that at these conditions of use, the engine noise is not prominent anymore (paragraph 2.2.3 in Chapter 2). Concerning the other driving situations *start up the motor*, *stop the motor*, *traffic light start*, *acceleration* and *traffic jam*, Diesel scores are really close. Indeed, a contrast analysis proves that those unsteady situations are not significantly different ($p < 0.05$) contrary to *hot idle* which is significantly different from other steady situations. For the following of the study it seems interesting to focus on the situation which best represents the Diesel character but on the two categories: the steady and the unsteady ones. Therefore, the choice of *hot idle* has established itself. However, the task is not so evident concerning the choice among the non-stationary driving situations. For several reasons exposed afterwards, *acceleration* appears to be a good candidate in order to focus on the Dieselness of this situation. Indeed, *start up the motor* and *stop the motor* are driving situations totally specific by their length (about 2s only). Concerning the three last driving situations *traffic light start*, *acceleration* and *traffic jam*, the first two obtain higher Diesel scores for C1 and C2. However, it is no longer the case for C3 since *acceleration* is really evaluated as being less Diesel than *traffic light start* and *traffic jam*. Moreover, just by focusing on the *acceleration* driving situation, the 6-cylinder vehicle is significantly different from the two other cars. In addition, the ANOVA analysis shows, for each vehicle, a significant difference between Diesel character of *hot idle* with the one of other stationary situations (with $p = 0.000$ for each interaction between *hot idle* and each steady situation);

A last noticeable result concerns vehicles' "hierarchy". By looking at situation by situation, 3-cylinder car appears to be the most Diesel one for *stop the motor*, *traffic light start*, *acceleration*, *deceleration*, *traffic jam*, *50-kph* and *70-kph*. For cases like *hot idle* or *90-kph*, the 6-cylinder car is judged more Diesel than the others, whereas for *start up the motor*, *110-kph* and *130-kph*, 4-cylinder one is evaluated more Diesel than others too. Therefore, there is no real tendency of the Dieselness evaluation of driving situations. This appraisal really depends on the interaction between the two factors: vehicle and driving situation. Also, let's be reminded that this experiment focuses on three particular vehicles, and we probably cannot generalize these results for all cars of lower, middle and upper classes (or of 3, 4 or 6 cylinder cars).

Let's focus on another point. Although the first purpose of this experiment is to know which driving situation best represents Dieselness, the **identification stage** allows us to focus on a methodology of road sign recognition. So, we can be interested in Dieselness evaluations given by participants who made the "wrong"[9] choice of road signs. Figure 5.8 presents in the same manner as Figure 5.7 mean scores and standard deviations of the twelve driving situations for the three cars C1, C2 and C3 for participants who made the "wrong" choice of road sign during the **identification stage**. Let's be reminded here that the **identification** and **evaluation** stages are totally independent.

[9] The term "wrong" is used in contrast with "right" term but, still one time, it does not represent a value-judgment.

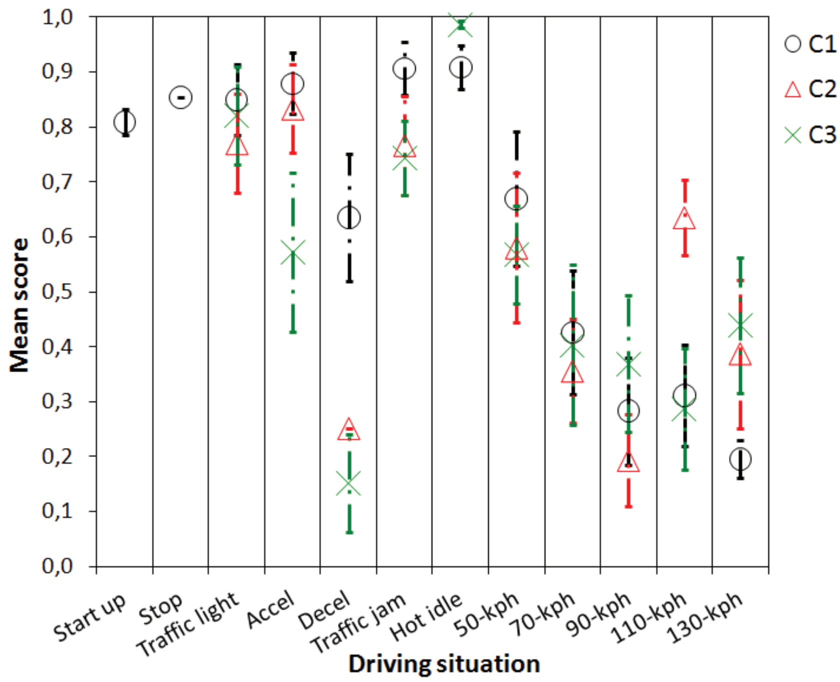


Figure 5.8: Dieselness mean scores and standard deviations of twelve driving situations for C1 (black round), C2 (red triangle) and C3 (green cross) for French participants who have chosen the "wrong" road sign during the **identification stage**.

First, for driving situations like *start up the motor*, *stop the motor* and *hot idle*, only one or two Dieselness scores are presented. Indeed, as we have already seen before, those three situations obtained a high percentage of recognition especially for C2 with 100% of success for *start up the motor* and *stop the motor*. Therefore, fewer results appear for these situations. Secondly, Figure 5.8 allows us to "join" the **identification** and **evaluation** stages by comparing results given for all reliable participants and those given by the ones who made the "wrong" choice during the recognition of road signs. Is the driving situation recognition important for assessing Dieselness? The calculation of Pearson coefficient allows us to conclude that for each car the appraisals of those two particular populations are strongly correlated with 0.98, 0.98 and 0.97 for C1, C2 and C3, respectively. Indeed, apart from a few differences between Figure 5.7 and Figure 5.8 (with some inversions for *traffic light start*, *50-kph* and *130-kph*), the Dieselness evaluations are really close. The "no-recognition" of driving situations does not influence the Dieselness appraisal. People can judge the Diesel character of a situation without necessarily recognizing it. However, let's remind ourselves that the two parts are totally independant. Would we obtain the same results with two parts not being separated? This question is not studied in this work but it is legitimate to ask it.

5.2.6 Summary and conclusion

The second stage of this listening experiment (**identification** one) allowed us to make sure of the good interpretation and recognition of steady and unsteady driving situations. The percentage of correct recognition for the driving situations at constant velocities lies typically between 20% and 40%. The discrimination between the different speeds (from *50-kph* to *130-kph*) is not an easy exercise. Concerning the unsteady ones, *traffic light start* and *acceleration* collect more incorrect choices. We have explained that these low percentages of correct answers by the fact that those driving situations sound very similar, and, therefore, they are difficult to distinguish. Finally, four road signs, but more precisely four labels (the ones of *start up the motor*, *stop the motor*, *deceleration* and *hot idle*), have certainly helped the recognition of these situations.

At last, the third stage of the experiment (**evaluation** stage) answered this goal: which driving situations best represent "the characteristic sound" of Diesel cars? The results proved that by taking into account the whole of driving situations, *hot idle* best represents Dieselness. However, as *hot idle* is a condition much studied by scientific community, especially by automotive workers, we decided to focus on another one and more particularly on an unstationary one: the *acceleration*.

5.3 Diesel driving situations: the German listening test

The Dieselness experiment is exactly the same in France and in Germany (same methodology, same sound reproduction, same task, etc.). For this reason we will not dwell on stimuli, apparatus and protocol which have already been detailed in their respective sections 5.2.2, 5.2.3 and 5.2.4. The interview realized at the end of the experiment, in order to gather information and impressions from each participant, was collected by a German colleague before translating verbalizations in English.

5.3.1 Participants

Thirty German participants performed this listening test. For the recruitment participants had to correspond to the same criteria as for French ones: they do not to work in automobile or acoustics domains, be a Diesel owner and use it regularly (daily or several times per week) and to be devoid of hearing problems. Table 5.4 summarizes information about the participants.

Men	Female	Age [yo]
19	11	30 (11)

Table 5.4: Data about German participants: number of men, of female, the mean age and standard deviation in brackets.

The German population is younger than French one. Indeed, for the German participants, the recruitment was realized among students of the Oldenburg University with 53% being between 20 and 25 years old.

5.3.2 Results and discussion

5.3.2.1 Identification stage: the road sign choice

Twelve road signs

This **identification stage** allows us to determine if naïve[10] participants are able to recognize driving situations only by listening to them. To compare German and French, Figure 5.9 presents percentages of those two populations for the good recognition of the road signs. Results are split into three charts which present each car, one by one: C1 at the left top, C2 at the right top and C3 at the bottom.

Let's focus on these three charts:

- C1: the most recognizable two situations are *start up the motor* and *stop the motor* for both the French and the German. *Start up the motor* is recognized up to 87% and 91% (for French and German participants, respectively) and *stop the motor* is well recognized at 91% and 100%, respectively. Also, by taking into account the twelve driving situations, the correlation coefficient between the two populations is 0.77 (going down to 0.47 for only steady situations and goes up to 0.92 for only unsteady situations). Finally, for all driving situations, except for *hot idle* and *130-kph*, German better recognize the situations than French;
- C2: in the same way as C1, *start up the motor* and *stop the motor* are the most recognizable situations with 100% of "success" for both populations (for the second situation only). Moreover, Germans better recognize the road signs than French here, too (except for *start up the motor* and *110-kph*). Also, by taking into account the twelve driving situations, the correlation coefficient between the two populations is 0.88 (going up to 0.92 for only steady situations and going down to 0.84 for only unsteady ones). Therefore, the recognition is more homogeneous between French and German for this car;
- C3: finally, the same conclusions can be done for C3 with the recognition of *start up the motor* (95% and 100% for respectively French and German) and *stop the motor* (100% and 95% for French and German, respectively). Also, Germans better recognize road signs except for *hot idle* and *stop the motor*. To

[10] The definition of this term has already been done p 40.

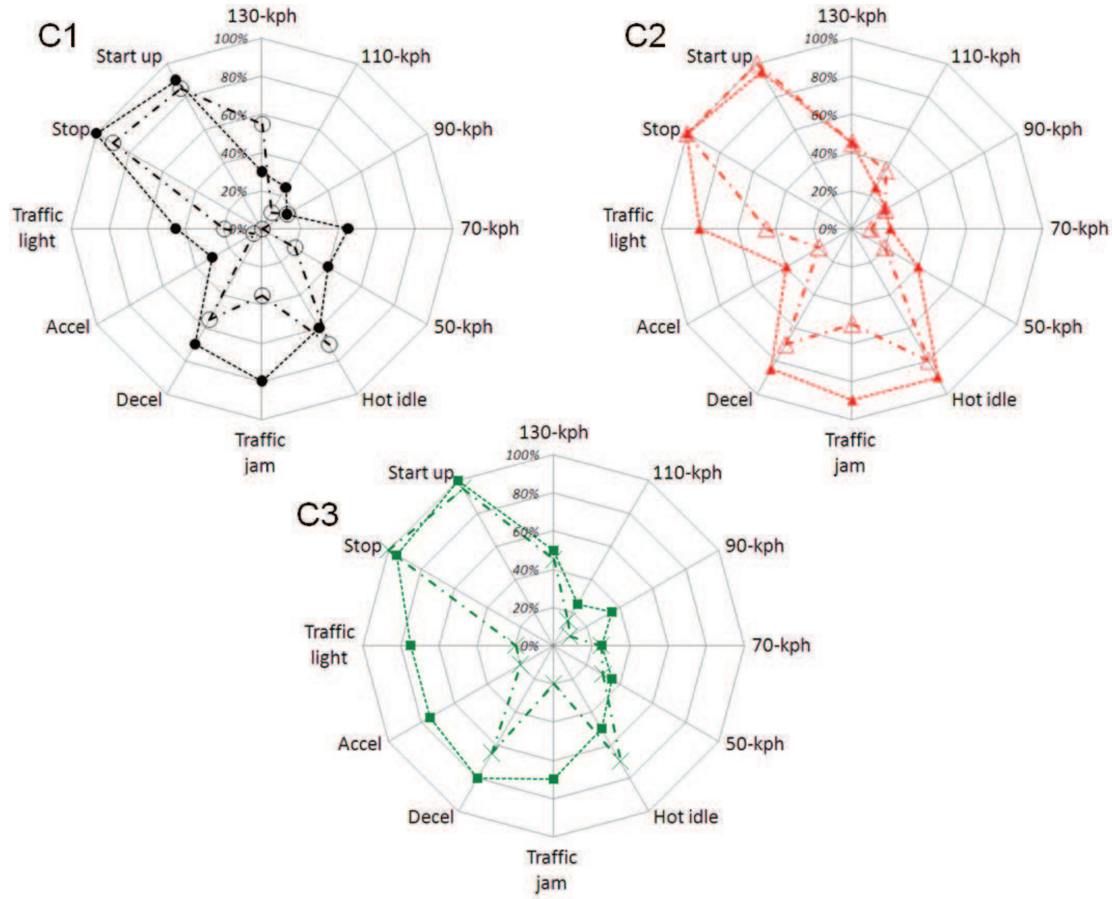


Figure 5.9: Percentage of French and Germans who chose the correct road sign for the twelve driving situations during the **identification stage** for C1 (at the left top), C2 (at the right top) and C3 (at the bottom). Results of French participants are respectively the black open circles, the red open triangles and the green crosses. Concerning the German ones, results are presented with filled black circles (C1), full red triangles (C2) and full green squares (C3).

conclude, the correlation coefficient between the two populations for all driving situations is 0.66 (0.80 and 0.94 for steady and unsteady situations, respectively).

As we can see for both populations, *start up the motor* and *stop the motor* are the most recognizable driving situations among the twelve proposed. Moreover, by taking into account all of these situations, the recognition results of French and German participants are closer, according to the evaluated car (with a correlation coefficient between 0.66 and 0.88).

Contrary to the remark given in paragraph 5.2.5.1 for French, *deceleration* and *hot idle* do not appear to be the most recognizable road signs after *start up the motor* and *stop the motor* for Germans. We have explained this phenomenon to be the result of the *deceleration* and *hot idle* road signs being more explicit than the other road signs. However, apparently, this particularity does not help Germans to recognize them better. Moreover, in the three cases C1, C2 and C3, the steady driving situations obtain the smallest percentages of recognition in spite of the explicit figures marked on road signs. This confirms the difficulty of discriminating different, close speeds only by hearing.

In the same way as for French participants, Table 5.5 presents the percentage of road sign recognition for the unsteady situations (at left) and for the steady ones (at right) for the three Diesel cars C1, C2 and C3. The grouping of the unsteady situations and of the steady ones on the other hand show that the unsteady situations are easily recognizable and especially in the case with German people.

Cars	Unsteady situations [%]	Steady situations [%]
C1	69	36
C2	82	40
C3	83	37

Table 5.5: Percentage of road sign recognition for the six unsteady and the six steady driving situations for Germans during the **identification stage**.

The thirteenth label

We focus here on the proportion of participants who used this label during the **identification stage**. In the same manner as in Figure 5.4, Figure 5.10 presents the percentage of participants who chose this label during the experiment. The same legend as in Figure 5.9 is used.

None of participants used this thirteenth label for *stop the motor* (for all vehicles), for *start up the motor* (only for C2) and for *traffic jam* (only for C1). For each car Figure 5.10 shows that:

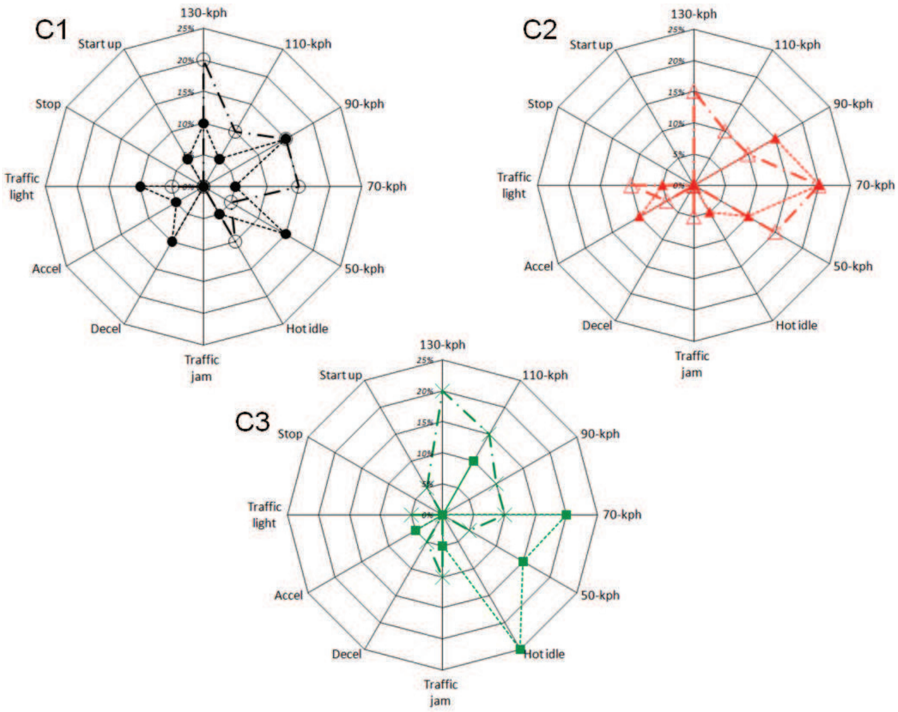


Figure 5.10: Percentage of French and Germans who chose the label “the sound does not correspond to any road sign” during the **identification stage** for C1 (at the left top), C2 (at the right top) and C3 (at the bottom). Results of French participants are respectively the black open circles, the red open triangles and the green crosses. Concerning the German ones, results are presented with filled black circles (C1), full red triangles (C2) and full green squares (C3).

- C1: concerning unsteady situations, the French did not choose this label except for *traffic light start* whereas German used it more. For the steady ones, both populations chose it except only 20% of the French for *130-kph*;
- C2: concerning unsteady situations, French did not choose this label except for the *traffic light start*, *acceleration* and *traffic jam*, whereas German used it less. This remark is still correct for the steady ones. Therefore, Germans seem not to choose this label for the 4-cylinder car;
- C3: concerning unsteady situations, Germans chose it only for *acceleration* and *traffic jam*, whereas the French chose it for the others too. For steady ones, as for all vehicles, this label is chosen more than

unsteady situations. However, we notice that Germans chose it with a proportion of 25% for *hot idle*, which represents the highest percentage of this label's use for all cars taken together.

Moreover, we notice that it has been chosen more for stationary situations than for unsteady ones which highlights the difficulty of discriminating the different steady speeds. Besides, the correlation coefficient for comparison of population gives 0.40 for C1, 0.60 for C2 and -0.15 for C3.

5.3.2.2 Evaluation stage: Dieselness evaluation

Preliminary analyses

In order to reduce the number of parameters and participants, the statistical analyses were realized in the same way as for French participants (cf paragraph 5.2.5.2 p 76):

- the calculation of Pearson correlation coefficients allows us to identify 18, 13 and 11 reliable participants for C1, C2 and C3, respectively. The participants obtained a correlation coefficient from 0.75 to 0.95 (for those who assessed C1), from 0.76 to 0.94 (for those who assessed C2) and from 0.74 to 0.91 (for those who assessed C3);
- the repeated-measure analysis of variance with three within-subject factors (2 Combinations, 3 Vehicles and 12 driving Situations) was performed. The three analyses for C1/C2, C2/C3 and C1/C3 are presented in Table 8.9 to Table 8.11 in Appendix F. Here too, the combination's order has no effect on Dieselness appraisal (1^{st} line of each table). Moreover, the different interactions with this combination factor (V x C and S x C) do not prove any influence either. So, the Dieselness appraisals for each car can be averaged since the combinations' order has no influence on the assessments. Therefore, we present results of Dieselness evaluations for each car taking into account the reliable participants (respectively for C1, C2 and C3).

Dieselness results

Figure 5.11 presents mean scores and standard deviations of the twelve situations for the three vehicles (3-cylinder car C1 with black round, 4-cylinder car C2 with red triangle and 6-cylinder car C3 with green diamond). We find the same order of driving situations from unsteady ones (*start up the motor* to *traffic jam*) to steady ones (*hot idle* to *130-kph*) for French participants.

A first remark concerns the use of the Dieselness scale. Indeed, Germans use it more broadly than the French. The lowest and highest German score (for all situations and all vehicles combined) are 0.24 and 0.97, respectively. For the French, the gap is only 0.56 of a point (between 0.33 and 0.89). Therefore, Germans consider most situations as more Diesel than the French think.

Influence of the vehicle

Figure 5.7 shows that the difference between vehicles is not so obvious for some cases. Indeed, we can see that the mean scores of *traffic light start* for C2 and C3 are very close (0.97 for C2 and 0.96 for C3) or even equal for *130-kph* between C1 and C3 (with Dieselness score of 0.22). This first remark is confirmed by the variance analysis which shows no significant influence of this factor on Dieselness appraisal (3^{rd} line of each table). So, the vehicle has no impact on Dieselness evaluation.

Influence of the driving situation

Scores are totally different according to the driving situation. So, the influence of this factor is confirmed by the variance analysis with respectively $F(11, 88) = 14.3$, $p < 0.01$ for C1/C2; $F(11, 88) = 14.1$, $p < 0.01$ for C2/C3 and finally, $F(11, 88) = 12.4$, $p < 0.01$ for C1/C3. Results show this factor's influence with the strongest effect among all factors and all interactions tested (R^2=64.9, 64.3 and 58.9 for C1, C2 and C3, respectively). According to the type of driving situation listened, Diesel character appears as being perceived differently.

Influence of their interaction (vehicle x driving situation)

By considering the mean scores obtained for each vehicle (Figure 5.11), the first three driving situations which best represent the Diesel engine for the Germans are: *stop the motor*, *traffic jam* and *hot idle* with 0.93 concerning C1, *traffic light start* and *hot idle* (0.97) and *traffic jam* (0.95) concerning C2 and *stop the motor* and *hot idle* (0.97) and *traffic light start* (0.96) concerning C3. The variance analysis highlights the influence of this interaction between vehicle and driving situation for Dieselness appraisal with $F(11, 88) = 1.3$, $p < 0.01$, $F(11, 88) = 2.2$, $p < 0.01$ and $F(11, 88) = 0.8$, $p < 0.01$ for C1/C2, C2/C3 and C1/C3. The vehicle's influence on Dieselness assessment depends on the driving situation.

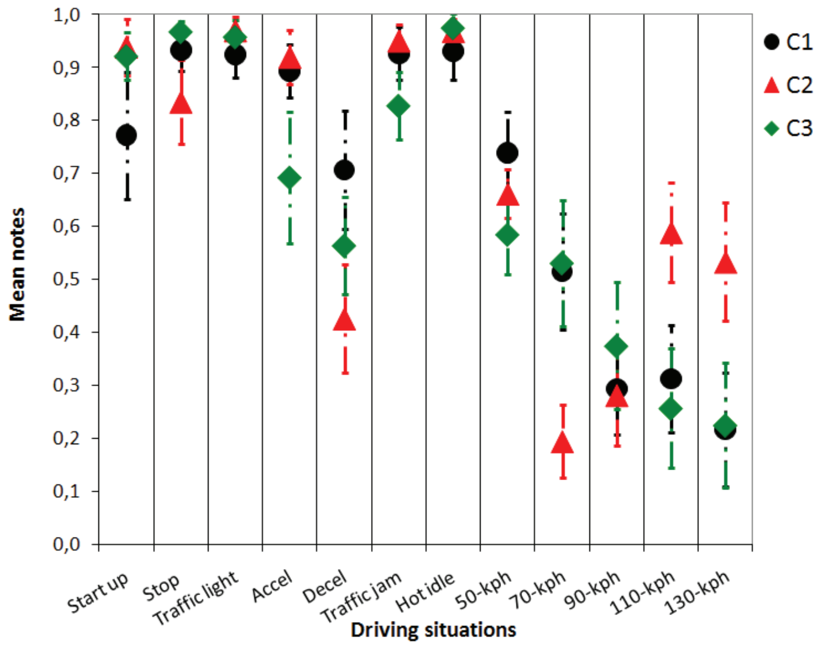


Figure 5.11: German participants: Dieselness mean scores and standard deviations of twelve driving situations for C1 (black round), C2 (red triangle) and C3 (green diamond).

For the three cars C1, C2 and C3, *hot idle* appears, here too, as a situation which best represents Dieselness. In the same way as French participants, all other situations obtain lower scores (especially the steady ones and *deceleration*). Concerning the other driving situations, a contrast analysis proves that *start up the motor*, *stop the motor*, *traffic light start*, *acceleration* and *traffic jam*, are not significantly different ($p < 0.05$). As for the French results, the Dieselness of *acceleration* is appraised as Diesel but not more Diesel than *stop the motor* or *traffic light start*, for instance. However, the same tendency is noteworthy: *acceleration* of a 6-cylinder car is not evaluated as 3- and 4- cylinder cars.

A last noticeable result concerns vehicles' "hierarchy". By looking at each situation by situation, the 3-cylinder car appears to be the most Diesel one for *deceleration*, *traffic jam* and *50-kph*. For cases like *stop the motor*, *hot idle*, *70-kph* and *90-kph*, the 6-cylinder car is judged more Diesel than the others, whereas for *start up the motor*, *traffic light start*, *acceleration*, *hot idle*, *110-kph* and *130-kph*, the 4-cylinder one is evaluated more Diesel than others too. Therefore, there is no real tendency for the Dieselness evaluation of driving situations. This appraisal really depends on the interaction between the two factors: vehicle and driving situation.

In the same manner as for French participants, we are interested in Dieselness evaluations given by participants who made the "wrong" choice of road signs. Figure 5.12 presents mean scores and standard deviations of the twelve driving situations for the three cars C1, C2 and C3 for participants who made the "wrong" choice of road sign during the **identification stage**.

Figure 5.12 allows us to "join" the **identification** and **evaluation** stages by comparing results given for all reliable participants and those given by the ones who made the "wrong" choice during the recognition of road signs. For *start up the motor* and *stop the motor* respectively, two and one Dieselness scores are presented. Indeed, as we have already seen before, these three situations have obtained a high percentage of recognition especially for C2 with 100% of success for *start up the motor* and *stop the motor*. Moreover, the calculation of the Pearson coefficient allows us to conclude that for each car the appraisals of those two particular populations are strongly correlated with 0.99, 0.91 and 0.86 for C1, C2 and C3, respectively. The correlation between scores obtained in Figure 5.11 and those obtained in Figure 5.12 is important but less than the French results. The

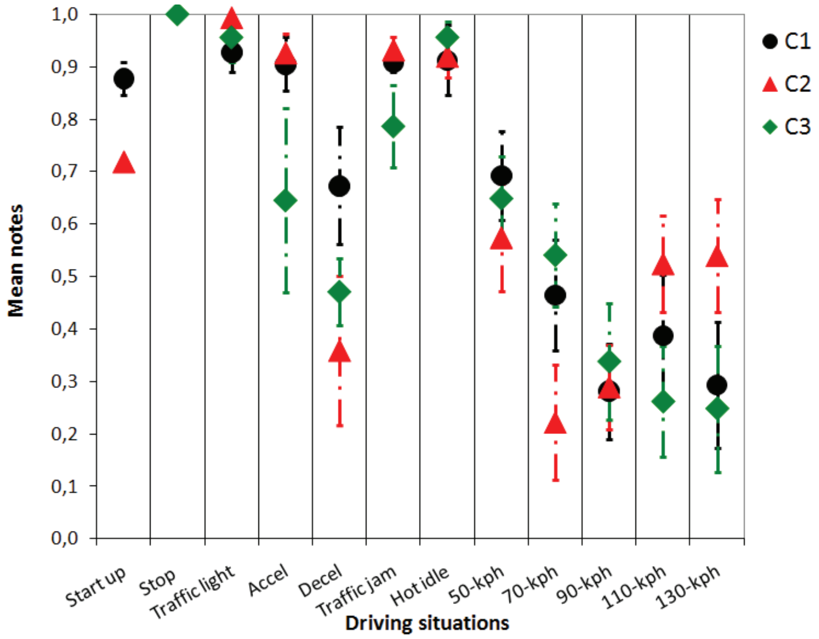


Figure 5.12: Dieselness mean scores and standard deviations of twelve driving situations for C1 (black round), C2 (red triangle) and C3 (green diamond) for German participants who have chosen the "wrong" road sign during the **identification stage**.

"no-recognition" of driving situations has no influence on Dieselness appraisal.

5.3.3 Summary and conclusion

Results of the second stage have shown that the percentage of correct recognition for steady driving situations did not give a lot of correct results. Indeed, it seems that the discrimination between the different speeds (from *50-kph* to *130-kph*) appears to be not so easy. Concerning the unsteady ones, percentages of recognition are better than the French. Indeed, for all unstationary situations, Germans recognize it better even for a 6-cylinder car with a rather good percentage.

As for French participants, the results of the third stage of the experiment (**evaluation** stage) has allowed us to make the choice of *hot idle* and *acceleration* for the following of the study.

5.4 Cultural influence on Dieselness assessment

A last mixed-model design ANOVA with one between-subjects variable (taking into account all of the participants) and three within-subjects variables was performed: S(P) x CO_2 x V_3 x S_{12}. The results are presented in the following tables (Tables 8.12 to 8.14) in Appendix G. In the same manner as in sections 5.2.5.2 and 5.3.2.2, we are interested in the influence of each factor (Combination order, Population, Vehicle, Driving situation and their interaction). Combination Order still has no influence.

Influence of the population

On the one hand for participants who assessed vehicles in the C1/C2 and C2/C3 combinations, there is no influence of the population on Dieselness appraisal. On the other hand concerning the C1/C3 combination, the population plays an important role: $F(1, 17) = 11.0$, $p < 0.01$.

Influence of the vehicle

The variance analysis shows no influence of this factor for the C1/C2 case. Concerning the two other combinations, results prove an impact of this one: $F(1, 17) = 7.1$, $p = 0.0162$ for C2/C3 and $F(1, 17) = 8.7$,

$p = 0.0091$ for C1/C3. Therefore, the vehicle has an influence on Dieselness evaluation for the two last cases. We notice that in those cases the common point is the presence of C3. Therefore, we can potentially conclude that this vehicle is unique compared to the others.

Influence of the driving situation

The influence of this factor is confirmed by the ANOVA analysis with $F(11, 187) = 45.7$, $p < 0.01$ for C1/C2; $F(11, 187) = 41.4$, $p < 0.01$ for C2/C3 and $F(11, 187) = 41.7$, $p < 0.01$ for C1/C3. Results show the influence of this factor with the strongest effect among all factors and all interactions tested (R^2= 52.4, 44.6 and 53.4 for respectively C1/C2, C2/C3 and C1/C3). According to the type of driving situation presented, Diesel character appears as being perceived differently.

Therefore, among the main tested factors: CO has no influence, P and V factors have one for some particular combination and S has a significant effect on Dieselness appraisal. Let's focus on their interaction.

Influence of their interaction

As we have seen in sections 5.2.5.2 and 5.3.2.2 for French and then for Germans, the interaction which shows some influence concerns the one between vehicle and driving situation. And indeed, this interaction still proves its impact on Dieselness evaluation with $F(11, 187) = 6.8$, $p < 0.01$; $F(11, 187) = 14.0$, $p < 0.01$ and $F(11, 187) = 5.5$, $p < 0.01$ for the different combinations C1/C2, C2/C3 and C1/C3. So, according to this, the vehicle's influence on Dieselness assessment depends on the driving situation. However, another interaction for the particular case of the combination C2/C3 appears to have a significant effect between population and driving situation with $F(11, 187) = 4.1$, $p < 0.01$, R^2= 4.5.

At first, taking an interest in sound perception of Diesel engine noise seemed to be a daunting task because it is very vague. This first experiment was therefore designed to define during which condition of use of a vehicle people feel the Diesel character of a vehicle. Also, this experiment was conducted in the two countries where there are the most Diesel vehicles in Europe: France and Germany.

Before concluding with the results for the characterization of the Diesel sound, let's show interest in the results of recognition of driving situations. Indeed, a recognition methodology of driving situation by a choice of road signs has been developed in the identification stage. For each stimulus the participant had to choose the road sign corresponding to the listening situation. The results show that the stationary situations are not easily discriminated for both French and German. For unsteady ones the recognition of situations, such as *start up the motor* and *stop the motor* seem to be more obvious. However, the participants do not succeed in making the difference between *traffic light start* and *acceleration*. This can be explained as follows: there are two situations very similar with two distinct road signs. This presents a lower probability of choosing the correct road sign.

Finally, the evaluation stage allows us to conclude about the driving situations which best represent the Diesel character: *hot idle* and *acceleration*. Indeed, unquestionably, *hot idle* is approved by a large majority for both French and German participants as being characteristic of Dieselness. By focusing on steady situations, none of the others are judged as Diesel. On the other hand, concerning the unsteady ones, the choice of another Diesel situation is a bit less obvious. First, *deceleration* is perceived totally different from the other five unstationary situations. Indeed, *start up the motor*, *stop the motor*, *traffic light start*, *acceleration* and *traffic jam* are the situations which best represent Dieselness just after *hot idle* with some different hierarchy depending on the evaluated car. However, it seems interesting to keep *acceleration* for the several reasons exposed in this chapter, especially since the 6-cylinder car is still evaluated as being less Diesel than two others for this particular situation. Last but not least, as for *hot idle* which is often studied in scientific articles or by automotive industries, *acceleration* and more generally time-varying sounds are often considered.

CHAPTER 6

Sound space of Diesel

The previous step allowed us to isolate driving situations which best represent the Diesel sound features with *hot idle* and *acceleration*. So, the second step of our study consists of focusing on those elementary driving situations in order to describe their particularities which make the Diesel identity.

As the Diesel source is described as a complex source (Chapter 2), the representation of its particular sound through a multidimensional approach [191] [192] appears to provide successful evidence for this quest. Indeed, it seems important to determine its sound dimensions which are relevant from a perceptual point of view. This approach is close to the one used in research works which focus on the musical domain with timbre studies (synthetized [113] or natural instrument tones [193]). Besides, American National Standards Institute defines timbre as *the attribute of auditory sensation in terms of which a listener can judge the difference of two sounds that are similarly presented and have the same loudness and pitch.* Timbre therefore is defined in a purely negative manner as everything that is *not* loudness, pitch and duration. Indeed, through the *timbre* notion we can distinguish a piano from a cello when they are played at the same level, on a same note and for the same duration. Therefore, the *timbre* term tends to have a well-defined meaning in the musical domain.

However, with complex sources, such as vocal or electronic sounds, it is more difficult to characterize them and, thus, describe their timbre. Besides, Schaeffer [87] and Chion [194] precise that the "traditional" definition of timbre is not sufficient anymore in this case[1]. They propose using more general terms as "sound object" or "sound material". As the examples cited above, Diesel is a complex source too. It is not totally tonal, even rather noisy, and for which, people have an *a-priori* knowledge. As a consequence, our study appears to be an extension of timbre study but for daily-life urban environment source.

So, after having defined the driving situations which best represent the typical sound of Diesel vehicles in Chapter 5, we focus on them in order to highlight their respective sound features. This chapter presents in the first part the multidimensional approach by precising the used model (paragraph 6.1). Then, we pursue with the presentation of the listening experiment and its results concerning the steady and unsteady situations *hot idle* and *acceleration* (paragraphs 6.2 and 6.3).

[1] As we will see in this chapter and in Chapter 8, the stimuli used during the different experiments were not equalized at the same level, at the same frequency or still with the same duration. Therefore, in our case, we can not speak about "timbre study". So, Chapters 6 and 8 present a multidimensional approach for the characterization of the Diesel source. We will not use the *timbre* term.

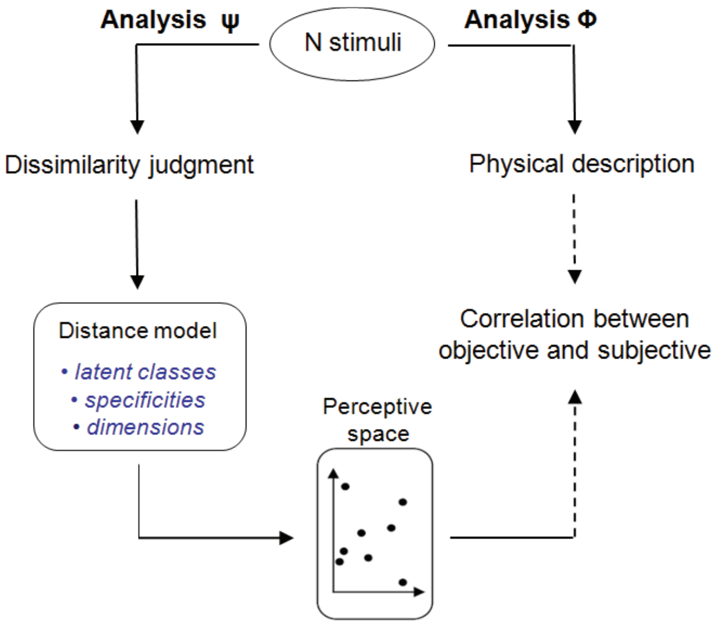


Figure 6.1: The two steps of analysis realized in parallel during a multidimensional study, the goal being to determine the correlation between the perceptual space and some physical attributes.

6.1 Multidimensional approach

A complex stimulus is generally characterized by several dimensions. In order to represent them, two main classes of models exist: the MultiDimensional Scaling (MDS) technique and the cluster analysis. The first one puts forward the hypothesis of continuous dimensions underlying the perception of stimuli while the second one gives a categorical structure of that same perception. However, these techniques constitute only descriptive approaches. Indeed, the representations resulting from these methods do not present a unique solution and the different dimensions have to be explained (notably by acoustic features represented through step II in Figure 6.1). In our case, the MDS method *CLASCAL* commonly used at IRCAM was chosen.

6.1.1 State of the art

Sounds are complex and they have, by acoustical and perceptive points of view, a multidimensional nature. In order to define their own features, various works have been realized on timbre in different domains: on air-conditioning sources [37] [38], on different automotive sounds [39] [40] [41] [42] but above all on musical instruments [34] [35] [36] [114] [115] [116]. Unlike pitch or loudness, it is difficult to describe timbre without first identifying its constituent parts. By using a MDS method, it is possible to interpret and to define the physical identity of dimensions. In other words, the method consists of identifying the common perceptual dimensions which underly the perception.

Concerning synthetic tones, the different experiments show the following results:

- for Grey et al. [113] [195] and Marozeau et al. [34], Spectral Centroid[2] and attack time (which depends on the beginning of sound, *i.e.* the rise time) appears to be the primary components of timbre without being able to interpret the third dimension of their results;
- Krumhansl [36], Krimphoff et al. [115], McAdams et al. [116] and Caclin et al. [196] conclude in a similar way and even manage to explain the third dimension as an irregularity in the spectral envelope;
- finally, other authors interpret their geometric spaces with parameters less reported, as spectral flux[3] [113] [116] or spectral spread [34] for instance.

The different conclusions imply that instrument recognition relies upon temporal and spectral information. The consistency of results across these various works indicates a high stability of perceptual processes related to the perception of musical tones. However, in the case of an experiment with sounds of road, air and rail transports [197] the extraction of acoustic parameters have not been able to explain the different dimensions of the perceptual space. This has been explained by the fact that the sound corpus was too heterogeneous to satisfy the continuum hypothesis and that the perceptual evaluation has been primarily made in terms of categorical (duality between MDS and cluster analysis as already mentioned above).

Some other research works go as far as using verbalizations of participants in order to interpret qualitatively the dimensions [151] [193] [198] [199] [200]. For most of the musical studies, the two verbal attributes "brightness" and "quality of attack" commonly characterize the timbre of these kinds of stimuli. In contrast, Grey and Gordon [195] propose a quantitative interpretation of "brightness" which is strongly correlated with Spectral Centroid. Moreover, others compare different techniques (Von Bismark [201] with Semantic Differential SD and MultiDimensional Scaling MDS[4]) or different models (Burgoyne et al. [202] [203] with *CLASCAL* and *Isomap*[5] or for Caclin et al. [196] with *CLASCAL* and *CONSCAL*[6]). The different results appear to be similar.

[2] Amplitude-weighted mean frequency of the energy spectrum, also named "brilliance".
[3] Degree of fluctuation of the spectral envelope.
[4] Indeed, with SD method, stimuli are appraised on several scales with opposite verbal attributes such as sharpness/rough-smooth or concentrated/diffuse [201]. In contrast, MDS is based on similarity (or dissimilarity) ratings. Both methods allow to find dimensions which extract a maximum of variance from the data.
[5] We let the reader to see the references for the explanation of *Isomap* method.
[6] In the same way as for *Isomap*, we do not explain the *CONSCAL* method.

6.1.2 MultiDimensional Scaling method

6.1.2.1 Definition

The MDS technique [204] [205] [206] allows a person to model the dissimilarity data in an optimum geometric model (named perceptual space). The methodology's goal is not to impose on participants a set of parameters with a view to appreciate an object, but to provide them with the possibility of finding particularities. Its advantages are (i) that it is based on easy and natural dissimilarity judgments for people (ii) there is no information on pertinent acoustic parameters and (iii) the dissimilarity representation is easy to understand.

From dissimilarity judgments of pairs of sounds, the MDS analysis builds a low-dimensional space in which, sounds are located with regards to their sound differences. The dissimilarity evaluations are processed by the algorithm which fits a distance model in which distances between sounds have a monotonic relationship to the judged dissimilarities [114].

The various models of MDS distinguish themselves from each other by two factors: the distances between stimuli and the inter-individual differences. We are not going to explain each technique in detail but we precise, for each of them one or several studies in which it is possible to reference: the "classical" *MDSCAL* [207] [208], the weighted Euclidean model *INDSCAL* [209], the one with latent classes *CLASCAL* [114], the extend one with common and specific dimensions *EXSCAL* [210] and the model used in this study with common and specific dimensions and latent classes which is an extend version of the *CLASCAL* model [114]. The *CLASCAL* algorithm reduces the number of parameters of *INDSCAL* by modeling weights not for individuals but for groups of participants called "latent classes".

6.1.2.2 CLASCAL model

CLASCAL [114] yields a spatial model by representing in a R-dimensions Euclidean space the dissimilarities between stimuli. The bigger the dissimilarity is, the bigger the distance between two stimuli is. Judgments of all paired-comparisons are grouped in a dissimilarity matrix. The *CLASCAL* model for the distance between two stimuli postulates common dimensions shared by all stimuli, the existence of additional dimensions specific to particular sounds (called "specificities") and differences between subpopulations of participants (called "latent classes"), which may be due to differences in perception or in judgment strategy. Those classes have different weights for each of the common dimensions and for the whole set of specificities. For the c^{th} latent class, the distance between two stimuli i and j within the perceptual space is thus computed according to:

$$d_{ij} = [\sum_{r=1}^{R}(w_{rc}(x_{ir} - x_{jr})^2 + \nu_c(s_i + s_j)]^{\frac{1}{2}} \tag{6.1}$$

with d_{ij}, the distance between stimuli i and j,
R, the number of dimensions,
w_{rc}, the weight attributed by the class c to the perceptual dimension r,
x_{ir} and x_{jr}, the coordinates of the stimuli i and j on the dimension r,
ν_c, the weight for class c on the whole set of specificities,
s_i and s_j, the values of specificities for stimuli i and j.

So, in summary, *CLASCAL* allows us to have a spatial representation of all stimuli on R dimensions, the specificity of each stimulus, the probability that each participant belongs to each latent class, and the weights of each perceptual dimension for each class[7].

Once the perceptual configuration is achieved, a physical interpretation of the space has to be given by finding relationships between stimuli characteristics (acoustic features) and their positions in spatial representation (perceptual dimensions).

6.2 Experiment

As we have seen in Chapter 5, *hot idle* and *acceleration* are the two steady and unsteady driving situations which best represent Dieselness. Therefore, the following work consists of focusing on sound space of those two "objects". We present here the experiment conducted for each of these driving situations.

[7] For more details about *CLASCAL* model, the reader could refer to studies of Susini [40], Winsberg [114] or of McAdams [116].

6.2.1 Participants

Two groups of participants performed the listening test: thirty-eight for the evaluation of *hot idle* and forty-one for *acceleration*. For the recruitment, participants had to meet some criteria. They had to have not worked in automobile or acoustic domains, to be a Diesel owner and use it regularly (daily or several times per week) and to be devoid of hearing problems (even if this criterion had not been checked). Table 6.1 summarizes information about the participants.

Situation	**Men**	**Female**	**Age [yo]**
Hot idle	19	19	42 (9)
Acceleration	22	19	44 (11)

Table 6.1: Data about participants (number of men, of female, mean age and standard deviations in brackets) which have evaluated *hot idle* (1^{st} line) and *acceleration* (2^{nd} line).

6.2.2 Stimuli

Stimuli correspond to two driving situations recorded in fourteen different cars (3, 4 and 6 cylinders from Lower to Upper classification). Those two driving situations correspond to *hot idle* and *acceleration* which were judged as being the situations most characteristic of Diesel sound in the previous experiment (Chapter 5). The fourteen vehicles used were the Hyundai Getz, Hyundai I10 and VW Polo with 3 cylinders in line (cf paragraph 2.2.2 in Chapter 2), Citroën C5, Fiat 500, Mercedes MC220, Peugeot 308, Renault Mégane (Diesel and gasoline[8]) and Renault Grand Scenic (Diesel and gasoline) with 4 cylinders in line, Citroën C6, Peugeot 407 Coupé and Renault Laguna Coupé with 6 cylinders in "V". All characteristics of those vehicles have already been presented in Table 4.2 p 58. Moreover, the recordings and the preparation of data[9] were exposed in sections 4.1.2 and 4.1.3.1 of Chapter 4. In addition, a fifteenth stimulus was presented to the participants. Indeed, in order to verify the importance of very low frequencies in automotive sound perception, Renault Mégane Diesel is presented twice: the original record and the same recording high-pass filtered at cutoff frequency $F_c = 70$ Hz. Therefore, fifteen *hot idle* and fifteen *acceleration* presentations are appraised by thirty-eight and forty-one participants, respectively in two different experiments. Table 6.2 presents the correspondence between the fifteen vehicles of the experiment and the number given to them in the following results.

The recording protocol is detailed in Chapter 4. Besides, loudness equalization was applied for *hot idle* stimuli. This was performed with a Matlab function which puts the different sound signals on the same loudness by basing on the sound with the smallest loudness. Two parameters have to be entered: the accuracy in sone (*i.e.* the accepted difference in sone between two sounds) and the maximum of iterations[10]. Concerning the *acceleration* ones, no treatments were made. Indeed, the loudness equalization of unsteady sounds is still the topic of several research studies today.

6.2.3 Apparatus

The experiment was performed in a soundproof booth at Renault with a Sennheiser half-opened electrostatic headphone (Chapter 4) and a subwoofer. Indeed, the low frequencies were reproduced with a HA-233 BOOSTER subwoofer from Haliaetus Technologies S.A.S[11] [211]. This HA-233 uses the technology of acoustic tailpipes [211]. Its streamlined shape allows for perfect aerodynamics and an enhanced rigidity, necessary to

[8] We have introduced two gasoline vehicles in order to focus on the position of this type of car among Diesel ones. Indeed, this choice was made following an experiment realized during the thesis on the perception of Diesel character with a corpus of two Diesel cars and two gasoline cars. The results showed that for driving situations like *hot idle*, *50-kph* and *stop the motor*, the gasoline vehicle may seem have a Diesel sound (Appendix I). Moreover, as the gasoline cars have a good image with the public, we chose two gasoline cars which are the matching cars to Diesel ones. Indeed, their only difference is the engine.

[9] The lengths of the stimuli are 5s concerning the *hot idle* and from 10 to 15s for *acceleration*. Indeed, the segmenting sound follows the engine revolution.

[10] This Matlab function has been developed taking into account the regulation DIN45631 based on the Zwicker's researchs. This regulation is based on the calculation of the basilar membrane's excitation.

[11] http://wwww.haliaeteus.com.

Vehicle	**Associated number**
Renault Laguna Coupé (V6)	1
Hyundai Getz (L3)	2
Peugeot 308 (L4)	3
Fiat 500 (L4)	4
Peugeot 407 Coupé (V6)	5
VW Polo (L3)	6
Hyundai I10 (L3)	7
Citroën C6 (V6)	8
Mercedes MC220 (L4)	9
Citroën C5 (L4)	10
Renault Mégane Diesel (filtered) (L4)	11
Renault Mégane Diesel (original) (L4)	12
Renault Mégane gasoline (L4)	13
Renault Grand Scenic Diesel (L4)	14
Renault Grand Scenic gasoline (L4)	15

Table 6.2: The fifteen stimuli of the *hot idle* and *acceleration* experiments with their corresponding number. L3: 3 cylinders in line, L4: 4 cylinders in line and V6: 6 cylinders in "V".

reproduce low frequencies ($f < 70$ Hz). So, this experiment was realized with participants seated on the simulation bench (paragraph 4.1.5.2 p 61). The sound signals were reproduced through the half-opened electrostatic headphone and the subwoofer from Haliaetus Technologies S.A.S.

6.2.4 Protocol

The test is made up of two parts: an **orientation** and an **evaluation** phase. First, the participant listens to all stimuli in a random order to familiarize himself with the variation range of sounds. Secondly, the **experimental** phase consists of two tasks. First, one pair of sounds is presented and after having listened to the pair (as many times as desired), the participant has to rate the dissimilarity between them on a scale from 0 at left ("Very similar") to 1 at right ("Very dissimilar"). The participant is asked to use the full scale in making his judgments. Then, for the same pair he has to choose his preferred sound by clicking on "Sound A" if he prefers the first stimulus of the pair or by clicking on "Sound B" if he prefers the second. After having validated the choices made for this pair with "Next pair", another pair is presented and so on for 105 pairs ($\frac{n(n-1)}{2}$, with $n = 15$ and excluding identical pairs). The instruction is presented in Appendix H.

6.3 Sound space of Diesel car: hot idle and acceleration

The data consisted of a vector of 105 paired comparisons for each of the driving situations. The steps for each analysis are exactly the same for *hot idle* and for *acceleration.*

6.3.1 Sound space of hot idle

6.3.1.1 Cluster analysis

In order to detect participants who have performed the experiment very differently from others, a cluster analysis is realized. Data sets that are systematically uncorrelated with all other sets indicate the participants who had not adopted a systematic rating strategy or those who misunderstood the experiment's instructions. Therefore, we eliminate these participants from further analysis.

The dissimilarity vector which groups together all participants who appraised *hot idle* is submitted to a hierarchical cluster analysis using the average linkage algorithm (cf Chapter 3 of Houix's thesis [212]). This analysis shows two participants excluded from the rest of the participants. Indeed, by focusing on their evaluations between 0.49 and 0.51, we notice that they certainly did not understand the instruction. Therefore, the multidimensional analysis is performed for thirty-six reliable participants.

6.3.1.2 Multidimensional sound space

The initial Monte Carlo analysis was performed on the null model (mean dissimilarities) to determine the number of latent classes of participants. The tests carried out for one to six classes reveal three latent classes (with 5, 17 and 14 participants, respectively). In addition, dimensions from one to six (with and without specificities, *i.e.* with or without the second member of the equation 6.1), have the lowest Bayesian Information Criterion[12] (BIC) corresponding to a spatial model with two dimensions and specificities. Table 6.3 presents the

	Without specificities		With specificities	
Dimension	**logL**	**BIC**	**logL**	**BIC**
1	-549	1254	1025	-1654
2	357	-426	1047	-1666
3	754	-1088	1154	-1647
4	902	-1251	1189	-1625
5	1059	-1434	900	-977
6	1098	-1380	990	-1025

Table 6.3: Hot idle: Log likelihood and BIC values for the spatial model of three latent classes for 36 participants and 15 sound stimuli.

log likelihood and BIC values for the spatial model with three latent classes from one to six dimensions. For this selected spatial model we obtain the coordinates of each stimulus along each common dimension (Figure 6.2), the specificity value for each stimulus and the weight of each latent class for each dimension (Table 6.4) through the *CLASCAL* model. However, by plotting the different spaces corresponding to each latent class with their

	Number of dimension	
Latent class	**1**	**2**
Class 1	1.20	1.43
Class 2	1.10	0.88
Class 3	0.71	0.69

Table 6.4: Hot idle: Estimated weights in the selected two-dimensional model with specificities for three latent classes.

own weight on each dimension, we noticed that the three spaces are really close to the average space (*i.e.* the one which takes into account all participants). This spatial configuration is shown in the two-dimensional projections in Figure 6.2. However, the three other perceptual spaces which take into account the weight of each latent class on both dimensions are presented in Appendix J.

The repartition of all stimuli of this sound space is homogeneous enough. We can distinguish four different groups (confirmed by a cluster analysis realized in parallel). First, we notice that the space is ranked per classification of vehicles: with $n°2$, 6 and 7 from Lower classification on the left side, with $n°13$, 4, 9, 11, 12 and 14 from the Middle one and $n°11$, 5, 8 and 10 for the Upper one. Moreover, the gasoline cars seem to be a bit different but without enlarging really the two-dimensional space. The groups by range of vehicles are especially correlated with the number of cylinders of the cars. Indeed, (i) the first group with $n°2$, 6 and 7 are 3-cylinder cars (ii) the second one regroups the 4-cylinder ones (iii) and the last one, the 6-cylinder ones (without $n°10$ which has only four cylinders). However, the repartition of $n°1$, 5, 8 and 10 is disparate and we can find an explanation by focusing on results of specificities. Indeed, they indicate the extent to which each stimulus is perceived as being different from all of the others along one or more dimensions or discrete features that are not shared by the whole sound set. The square roots of these values are comparable in magnitude to the coordinates of the stimuli along the common dimensions. The specificities for the stimuli $n°1$, 5, 8 and 10 are 0.21, 0.11, 0.07 and 0.07, respectively. Therefore, the different situation of Renault Laguna Coupé can be explained by its specificity value.

[12] It is linked to the log likelihood [213] and it is used to select the most parsimonious model that best fits the data.

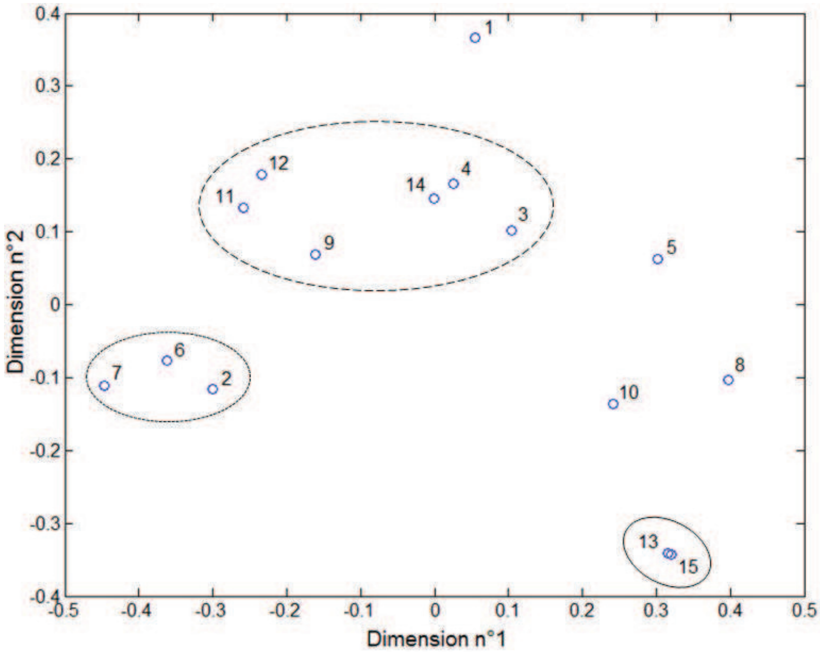


Figure 6.2: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *hot idle* and for the 36 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

Moreover, the choice of testing two other parameters was made during the preparation of the experiment: the influence of a subwoofer during a perceptual test (with the introduction of Renault Mégane original and high-pass filtered versions) and the position of gasoline cars compared to Diesel ones. So, with this first perceptual sound space we can conclude that there is no influence of the subwoofer during a perceptual listening test (with the close position of stimuli $n°11$ and $n°12$). Moreover, concerning the perceptive place of two gasoline cars among thirteen Diesel ones, another *CLASCAL* analysis was performed in which the two gasoline vehicles were removed. It shows that the new two-dimensional space is still homogeneous without big differences.

Acoustic analyses

The next step consists of determining the acoustic and psychoacoustic parameters that characterize the common perceptual dimensions. To succeed in this approach three steps are necessary: (i) first, we start listening to the stimuli in terms of their relative positions in the multidimensional space in order to have an idea about the kind of perceptual variation that corresponds to each dimension, (ii) then, hypotheses about acoustic or psychoacoustic descriptors are made and (iii) finally, these are computed[13]. A good correlation between the descriptor and the perceptual dimension is taken as indicator of a good candidate that well explains this dimension.

Besides, the first dimension of the *hot idle* sound space can be explained by the engine revolution speed [RPM], *i.e.* the pitch, with a correlation coefficient of 0.70. However, the best descriptor explains this dimension with a correlation coefficient of 0.81: the modulation frequency[14]. Indeed, the calculation of this parameter was made on different octave: 1000, 2000 and 4000 Hz. The results show that this is the octave 1000 which has the best correlation with the first dimension (coefficient correlation of 0.81) against 0.70 and 0.74 for octave 2000 and octave 4000, respectively. Figure 6.3 presents the linear regression between the dimension $n°1$ and this acoustic feature.

Therefore, this first result confirms the modulation from this type of driving situation which characterizes

[13] The different acoustic and psychoacoustic parameters have been computed with different tools from Genesis (Loudness Toolbox: http://www.genesis-acoustics.com/), Head Acoustics (Artemis: http://www.head-acoustics.de/) or IRCAM (Ircam Descriptor at http://wiki.rd.ircam.fr/).

[14] Cf paragraph 3.2.1.4 p 44.

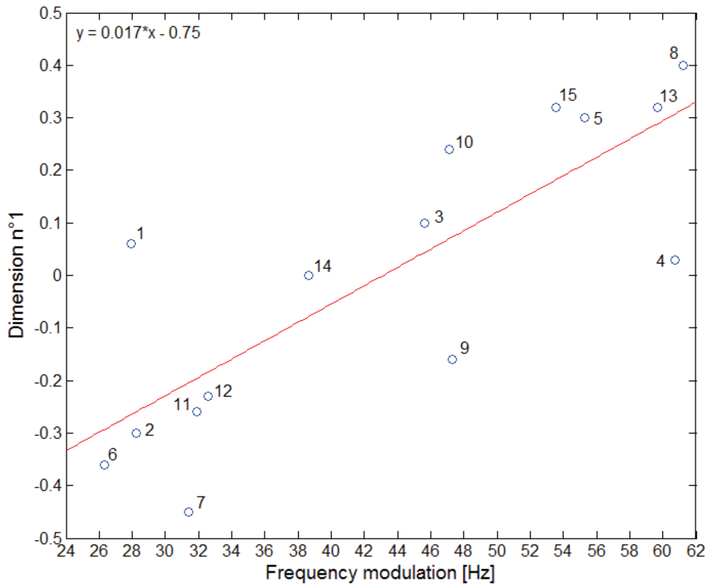


Figure 6.3: Linear regression between dimension $n°1$ and the modulation frequency. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

it and is often treated in scientific literature [19] [20] [171]. Indeed, in Figure 6.2 if we "follow" the dimension $n°1$ from the left to the right (*i.e.* from stimulus $n°7$ to the $n°8$), we move from vehicles with a lot of modulation toward cars of upper classification which sound "smoother". Also, the dimension $n°2$ appears to be more difficultly explained with only one descriptor. Therefore, some results present a multiple linear regression which shows the influence of different independent variables (acoustic and psychoacoustics descriptors) on the dependent variable (the considered dimension). The chosen multiple regression is the *Backward* model[15]. This method begins by entering all terms specified on the stepwise list into the model. At each step the least significant stepwise term is removed from the model until all of the remaining stepwise terms have a statistically significant contribution to the model. At first by listening the sound space along the dimension $n°2$, it is not obvious to find the evolution of an acoustic feature. So, we have sought to obtain the best model which approximates this dimension with various parameters. Different descriptors have been calculated: loudness, modulation frequency, sharpness, engine revolution speed, roughness, fluctuation strength, spectral centroid, perceptual spectral centroid, specific emergence and spectral spread (cf to the definitions detailed by Peeters [214]). Before calculating the best model which approximates this dimension, we have verified the possible correlations between these different parameters in order to limit their number in the SPSS *Backward* model. The results show that two descriptors contribute to approximating the 2^{nd} dimension with a correlation coefficient of 0.42. Therefore, the dimension $n°2$ is approximated by the following equation:

$$y = -0.008x_1 - 0.425x_2 - 0.098 \tag{6.2}$$

with x_1, being the modulation frequency and x_2, being the specific emergence[16].

Preference study

The final stage of the study aims at modeling the preferences of participants. The method consists of having a preference matrix of binary judgments for each participant. Indeed, the binary judgments indicate yes or no if the stimulus A was preferred to stimulus B in the pair [A,B].

[15] One of the different models proposed by SPSS software among *Enter*, *Forward*, *Stepwise* and *Remove* ones. It is well explained at http://www.helsinki.fi/ komulain/Tilastokirjat/IBM-SPSS-Spec-Regression.pdf.
[16] These parameters are defined in paragraph 3.2.1.4 p 44.

The data reduction of this experiment part was performed with *PRESTOOL/Consensus* model [215], commonly used at Renault. This model allows us to find the consensus (hence its name) that summarizes the best judgments of participants on a set of products (our fifteen stimuli here). *Consensus* provides three main results: the ranking of preferences which underlies all the judgments expressed by one participant, the same ranking expressed by all participants and sub-populations of participants whom the opinion diverges, if they exist. Several types of statistical evaluation are possible. In our case we chose to use this tool taking into account the data from each participant (given by the "median" criterion). This test was used to assign each participant to one dimension of preference and allows us to find the different sub-populations. Finally, the number of dimensions that we choose determines the number of sub-populations that we want to retrieve.

The different analyses undertaken with one, two and three dimensions are summarized in Table 6.5. They

Dimension	Error rate [%]	Sub-population (Number of participants)
1	30.8	-
2	26.7	6 and 30
3	26.7	5, 25 and 6

Table 6.5: Error rate and number of participants for each sub-population for the three analyses undertaken with one, two and three dimensions for *hot idle* experiment.

give an error rate of 30.8%, 26.7% and 26.7%, respectively. This error rate corresponds to the information which is not well represented in the solution.

It takes principally into account the inversions' rate[17]. The analyses with two and three dimensions allow us to have sub-populations of 6 and 30 for the first case and of 5, 25 and 6 for the second one. The preference rankings obtained in the first analysis (with only one dimension) and in the second one (with the group of 30 participants) are really similar, even if the error rate is a bit bigger for the one-dimensional representation. Therefore, we present below the preferences ranking with only one dimension.

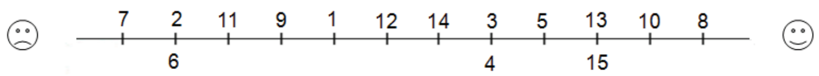


Figure 6.4: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the 15 stimuli of *hot idle* and for the 36 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

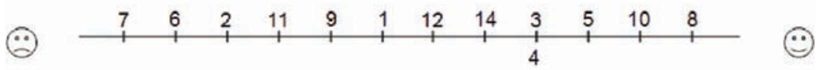


Figure 6.5: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the 13 stimuli of *hot idle* and for the 36 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original) and 14: Renault Grand Scenic.

The more we follow the preference dimension towards the $n°8$ in this example, the more the participant has said that he preferred the stimulus. As we can see in Figure 6.4 in comparison with Figure 6.2, the preference is linked to the modulation frequency. The more there is modulation the less the participant likes this.

[17] There is an inversion when the participant says that he prefers the stimulus A to the stimulus B and that the preference's classification on the dimension gives a "best" position for B. Also, the *"non-differentiated preference"* is taken into account if the participant prefers one of the two presented stimuli and that the result give an *ex-aequo* between those two stimuli.

We can find again the three groups of vehicles with $n°2$, 6 and 7 from Lower classification on the left side, with $n°3$, 4, 9, 11, 12 and 14 from the Middle one and $n°5$, 8 and 10 for the Upper one close to the gasoline vehicles $n°13$ and 15. The difference comes from the stimulus $n°1$ (Renault Laguna Coupé) which is not really appreciated. Finally, as for MDS representations, we are interested in results given when we do not take into account the gasoline vehicles $n°13$ and 15. The ranking obtained is exactly the same as we can see on Figure 6.5. There is no influence of the gasoline cars in the preference ranking. They have been preferred among other Diesel cars as $n°5$, 10 and 8 for instance, but they do not disrupt the rest of the ranking even by removing them.

It should be noted here that we could have also use more conventional approaches for the analysis of the results of preference: similar approaches such as Thurstone or Bradley-Terry-Luce. The Thurstone method uses a normal distribution and gives results in the form of intervals (as done here). The BTL method gives its results in the form of a ratio. It would be interesting to use one of these methods (or even the two) on the data in order to compare the preference results.

6.3.2 Sound space of acceleration

6.3.2.1 Cluster analysis

In the same way as for the *hot idle* results, the same cluster analysis was performed for the forty-one participants who have evaluated *acceleration*. The analysis shows that three participants are uncorrelated with the rest of participants. Indeed, by focusing on their evaluations, we noticed that they certainly did not understand the instruction because their evaluation fluctuate between 0.49 and 0.51 for two of them or was left equal to 0 for the third one. Therefore, the multidimensional analysis was performed on the thirty-eight reliable participants.

6.3.2.2 Multidimensional analysis

In the same way as for the *hot idle* analysis, the tests for determining the number of latent classes and the number of dimensions was performed. These reveal three latent classes (with 4, 12 and 22 participants) and two dimensions for the case with specificity. As for the *hot idle* case, Table 6.6 presents the log likelihood and BIC values for a spatial model with three latent classes from one to six dimensions. In addition, we obtain the

	Without specificities		With specificities	
Dimension	**logL**	**BIC**	**logL**	**BIC**
1	814	1785	564	-830
2	82	126	745	-1059
3	472	-521	685	-807
4	521	-486	770	-844
5	656	-623	653	-477
6	667	-513	638	-314

Table 6.6: Acceleration: Log likelihood and BIC values for spatial model of three latent classes for 38 participants and 15 sound stimuli.

coordinates of each stimulus along each common dimension (Figure 6.6), the specificity value for each stimulus and the weight of each latent class for each dimension (Table 6.7). Contrary to the sound space of *hot idle*,

	Number of dimension	
Latent class	**1**	**2**
Class 1	0.66	1.58
Class 2	1.26	0.83
Class 3	1.08	0.59

Table 6.7: Acceleration: Estimated weights in the selected two-dimensional model with specificities for three latent classes.

one represents in Figure 6.6 the two-dimensional sound space for one class, the third one with twenty-two participants (*i.e.* by taking into account the weight of the first latent class on both dimensions). Moreover, the first class contains only four people and is not representative of the majority of evaluations. The other sound spaces obtained are very close with the average one taking into account all participants and the one taking into account the weight of the second latent class. All of those other perceptual sound spaces are presented in Appendix J.

In this case, the repartition of stimuli on the space is less homogeneous and the vehicles are less distin-

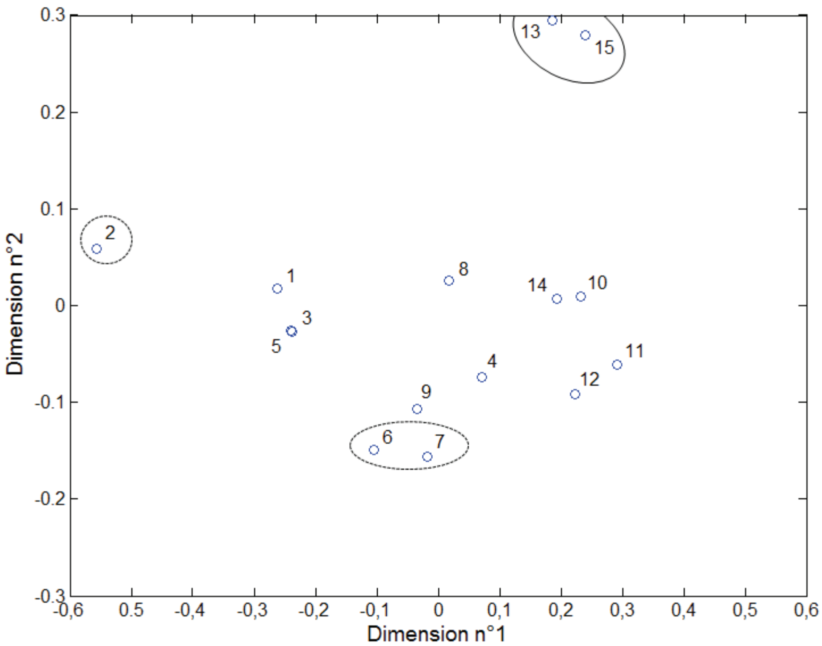


Figure 6.6: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *acceleration* and for the third class of 22 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

guished than in the *hot idle* case. Indeed, the groups of vehicles highlighted in Figure 6.6 have changed here. There is no longer Lower, Middle and Upper cars. Only the gasoline cars ($n°13$ and 15) are perceived different from the others but still are similar between themselves. This result shows that in this *acceleration* case people can distinguish Diesel from gasoline vehicles. This difference may be found in the sporty character of gasoline ones [15] [216] [11] [56]. Concerning the 3-cylinder cars $n°2$, 6 and 7, the group is split. The sound of VW Polo ($n°6$) and of Hyundai I10 ($n°7$) seem to be close to the majority of the sound corpus. Dimension $n°1$ explains the difference between Hyundai Getz ($n°2$) from all others whereas dimension $n°2$ explains the distance between Diesel and gasoline cars. This discrepancy is highlighted in the results of specificities with 0.04 and 0.00 for respectively $n°13$ and 15. Moreover, by modeling the sound space without taking into account the two gasoline vehicles, the new space is totally elongated along the 2^{nd} dimension but with the same coordinates along the 1^{st} one. Concerning the influence of subwoofer, still here, there is no big difference between $n°11$ and 12.

Acoustic analyses

In the same way as for *hot idle* case, acoustic and psychoacoustic parameters are calculated in order to check a potential link between each of them and each dimension of the perceptual space. Here too, we focus on the sound space with fifteen stimuli. Three parameters, which are strongly correlated between themselves because they represent the unstationary loudness, well explained by the first dimension. Indeed, N5, N10 and STLmax (cf footnote p 41 in Chapter 3 for the definitions of those parameters) correlate well with correlation coefficients of -0.93, -0.93 and -0.91, respectively. Figure 6.7 presents, as for the *hot idle* case (cf paragraph 6.3.1.2), the linear regression between the first dimension and the three unstationary loudness cases N5 (a), N10 (b) and STLmax (c). Therefore, it is not surprising to find that the three acoustic features explain one of the two

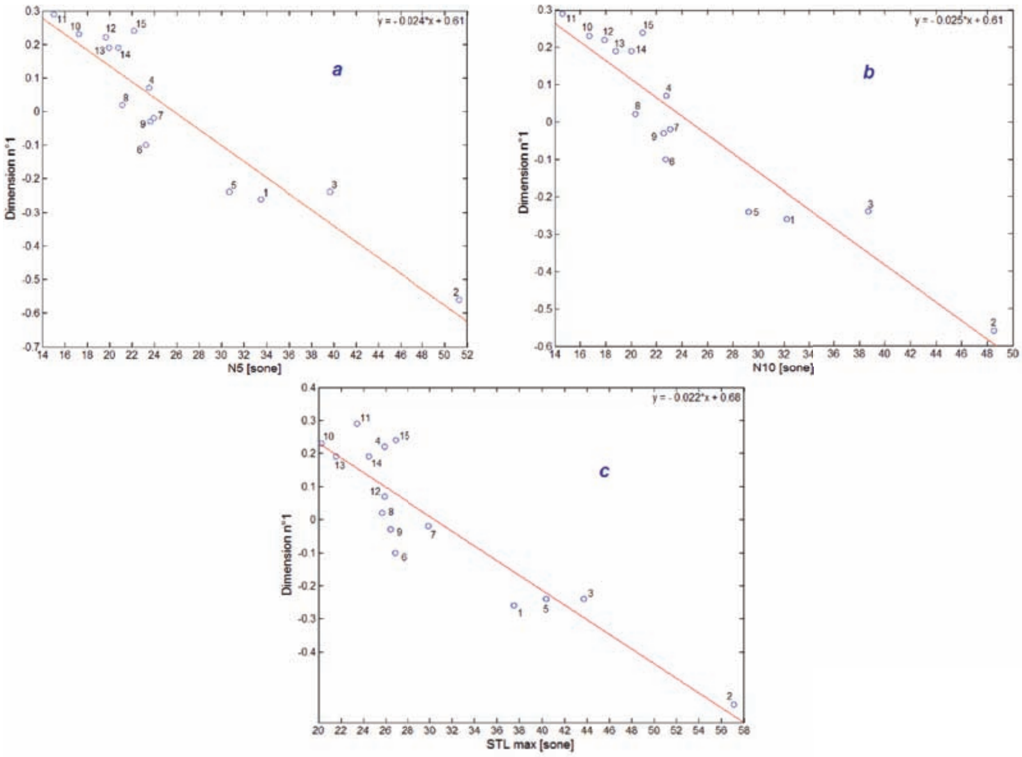


Figure 6.7: Linear regression between dimension $n°1$ and N5 (a), and N10 (b) and STLmax (c). Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

dimensions. As we did not equalize the loudness of the different *acceleration* presentations, the parameters distinguish the vehicles at order 1 [163] [159] [160]. Concerning the dimension $n°2$, the analysis steps are performed in the same way as for *hot idle* (cf paragraph 6.3.1.2). However, in this case the results are not so obvious. Indeed, the best model obtained for this driving situation gives a correlation coefficient of 0.44 by taking into account two descriptors: the averaged envelope and the length before the gear change[18].

By taking into account the four descriptors cited above, the model improves the coefficient correlation to 0.48 but this solution is not explicit because $p = 0.13$. Moreover, an ANOVA analysis confirms the significance of the chosen model (with two descriptors) with $F(2, 14) = 4.79$, $p < 0.01$. The dimension $n°2$ is approximated by:

$$y = 0.1x_1 + 0.23x_2 - 0.36 \tag{6.3}$$

with x_1, the length before the gear change,
and x_2, the averaged envelope.

Preference study

In the same way as for *hot idle*, the different analyses undertaken with one, two and three dimensions are summarized in Table 6.8. The different analyses give an error rate of 20.5%, 19.8% and 18.0%, respectively. The analyses with two and three dimensions allow us to have sub-populations of 3 and 35 for the first case and 2, 15 and 21 for the second one. The preference rankings obtained in the first analysis (with only one

[18] As precised in Chapter 4, the *acceleration* stimuli have been presented with a change of gear between the 2^{nd} and the 3^{rd} one. Therefore, the calculation of the length before and after this change has been calculated.

Dimension	Error rate [%]	Sub-population (Number of participants)
1	20.5	-
2	19.8	3 and 35
3	18.0	2, 15 and 21

Table 6.8: Error rate and number of participants for each sub-population for the three analyses undertaken with one, two and three dimensions for *acceleration* experiment.

dimension) and in the second one (with the group of thirty-five participants) are really similar even if the error rate is a bit bigger for the one-dimensional representation. Therefore, we present the preferences ranking below with only one dimension.

As we can see in Figure 6.8 in comparison with Figure 6.6, the preference is linked to the dimension $n°1$

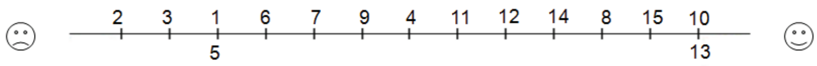


Figure 6.8: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the 15 stimuli of *acceleration* and for the 38 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

of the sound space which is characterized by the unsteady loudness N5, N10 and STLmax. Besides, Table 6.9 classifies the vehicles from the highest level (top of the table) towards the weakest one (bottom of the table) of N5, N10 and STLmax. This classification allows us to understand if one of these parameters has a stronger impact than the others on the preference ranking.

As we can see, the first half of preferred vehicles (left half in Figure 6.8 and first half at the top of

N5	N10	STLmax
2	2	2
3	3	3
1	1	5
5	5	1
7	7	7
9	4	15
4	6	6
6	9	9
15	15	12
8	8	4
14	14	8
13	12	14
12	13	11
10	10	13
11	11	10

Table 6.9: Classification of the 15 vehicles from the highest level of N5, N10 and STLmax (top of the table) towards the weakest one (bottom of the table). This table has to be compared with Figure 6.8.

Table 6.9) are well explained by the three parameters. The more there is some sound level, the less the participant appreciates the vehicle. However, for the rest of the cars it is less obvious. It is not easy to distinguish the cars $n°8$, 10, 11, 12, 13, 14 and 15 which are regrouped in Figure 6.6. These vehicles are the two gasoline ones, the two Diesel ones which match to gasoline ones[19] and the Citroën C5 ($n°10$) and C6 ($n°8$). Therefore, as we have already said, the two Citroën belong to the Upper classification of vehicles and it almost reassuring to find them among participants' preferences. However, the result concerns all others which are only Renault. Therefore, Diesel cars are appreciated as the gasoline ones and those of upper classification.

Finally, as for the *hot idle* case, there is no change of ranking without taking into account gasoline cars (Figure 6.9). There is no influence of the gasoline cars in the preference ranking. They have been preferred

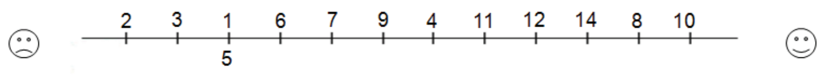


Figure 6.9: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the 13 stimuli of *acceleration* and for the 38 participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original) and 14: Renault Grand Scenic.

among other Diesel cars as $n°5$, 10 and 8 but they do not disrupt the rest of ranking even by removing them.

As I have already mentioned before, it would be interesting to use Thurstone or BTL methods in order to compare the preference results with these ones.

[19] The only difference between the two Renault Mégane and the two Renault Scenic is the engine. For both, we have the gasoline and the Diesel ones.

This chapter presented results of a multidimensional approach in which we have focused on the two driving situations chosen as being the most representative of Dieselness: *hot idle* and *acceleration*.

Besides, concerning the *hot idle* case, the dissimilarity experiment allowed us to obtain a two-dimensional perceptual sound space with the first dimension well explained (correlation coefficient of 0.81) by the modulation frequency and a second one approximated by a linear combination of specific emergence, loudness, length and fluctuation strength. The first result confirms the different studies performed on sound of Diesel *hot idle*. Moreover, as we have expected, there is a strong correlation between this modulation and the preference. Indeed, the more there is modulation, the less the participant prefers the case. This modulation feature is characteristic of the 3-cylinder cars, so, this type of vehicle suffers from its engine geometry which creates an irregular sound (cf paragraph 3.2.1.2 p 43).

On the other hand, the first results of multidimensional scaling for *acceleration* give a two-dimensional perceptual sound space here too. However, the two dimensions are explained (i) by the unsteady loudness N5, N10 and STLmax with correlation coefficient of -0.93, -0.93 and -0.91, respectively and by (ii) a combination of mean loudness and length before the gear change. The first result still represents the parameter at order 1 which characterizes the unsteady stimuli in various experiments treated in the scientific literature. Finally, the preference is explained by the different descriptors of loudness because the higher the sound level, the less the participant appreciates the vehicle.

Finally, after having obtained the respective sound space for *hot idle* and *acceleration* with the parameters which can explain the preference evaluation, we will continue with the same approach in Chapter 7 by introducing the vibrations. In this case, we want to know if vibrations of the seat and the steering wheel have some influence on the perceptual sound space and on preference appraisals. For different reasons exposed in the following chapter, we will focus on only one driving situation: the *acceleration*.

STEP II

INFLUENCE OF VIBRATIONS ON DIESEL PERCEPTION

Harmony of forms and sounds . . .
when Art and Technology meet, it is still a matter of vibration.

Chapter 7

Vibrations' influence on Dieselness perception

This chapter is an exact reproduction of an article submitted in Applied Acoustics. The first sections such as the introduction (cf paragraph 7.1) and the database of sound and vibrations (cf paragraph 7.2) include some information already detailed in the previous chapters.

Chapter 7 presents an abstract, an introduction which contains and confronts various scientific studies about interaction between sound and vibrations, a detailed description of the recordings of sound and vibrations and their reproduction on a bench and, finally, the perceptive experiment and its results.

Up to now, different studies dealing with vibrations' influence on acoustics have been, in most cases, realized on global annoyance. In our case, the present study examines the vibrations' influence on the auditory perception of Diesel character (called Dieselness in this article) of a vehicle. In addition, cultural experience is evaluated by testing two groups of Diesel owners from two European countries (respectively France and Germany). During the experiment, each population was exposed to sound only, and sound and vibrations simultaneously. This perceptual test was realized on a vibration bench (driver seat and steering wheel) with headphones. Three kinds of vehicles and six different driving situations have been tested. Results reveal no differences between French and German. Also, the adding of vibrations influences the Dieselness evaluation. The participants gave slightly higher scores (more Diesel) or equal (as Diesel) with vibrations than without. However, this vibration effect is slightly dependent on the type of vehicle and on the driving situation. Moreover, it is less important for Germans. In addition, for each group of participants, the other factors, vehicle and driving situation, have an effect on the Dieselness assessment. The effect of the vehicle allows us to show that a 3-cylinder car is significantly different from 4-cylinder and 6-cylinder cars. Finally, the interaction between the driving situation and the vehicle shows the strongest effect on Dieselness evaluation, among all interactions tested. The vehicle effect is dependent on the driving situation. All results and conclusions have to be taken with care in order not to generalize for all similar classification cars.

7.1 Introduction

Even without taking into account sound, vibration perception is a very complex topic. Indeed, different random parameters, like postures and participants' sensitivity contribute, among others, to this perception. In addition, the main reason for this topic's complexity lies in the difficulty to reproduce the details of previous studies. There is a great disparity between various experimental contexts [48] [120] [128]: level and dynamics of vibrations, artificial or real sources, frequency range of stimuli or test methodologies.

The common basis for studies about vibrations is the use of a bench made up of a platform with a seat and, sometimes, even a steering wheel [65] [25] [217]. Nevertheless, the different authors do not take into account the same degrees of freedom: a majority limit their vibration reproduction in the vertical plane along the z-axis for the seat [46] [47] [125].

By taking into account the whole of the modalities, the possibilities of experiments are numerous: vibration's effect on noise assessment, effect of sound stimulus on vibration appraisal or, also, effect of both on the overall evaluation of a parameter (such as comfort [123]). Most studies about this interaction focused on the influence on the perception thresholds (of sound or vibrations) [218] [144]. Indeed, studies of Weber et al. [144] and Bellmann [6] conclude that there is no significant influence of sound on the perception thresholds of vertical vibrations. With a study about vibrations influence on the loudness assessment, Parizet et al. [125] show the lack of vertical vibration's influence on this loudness evaluation. Conversely, they indicate that a sound stimulus significantly impacts the vibration's level assessment. Besides, Amari [141] evokes a *"synergistic effect"*: the higher the noise level, the higher the vibration level is considered. In a different register with the influence of sound on vibration's level assessment, Miwa and Yonekawa [142] showed that there is no significant effect on it. However, they join Parizet's conclusion that with a high noise level, the vibration level is overestimated.

Other kinds of studies focused on discomfort (or annoyance) assessment [48] [124] [26] [121], especially for idle driving situations ([26] [46] [65] [25] [27] [120]). It has been observed that both modalities can contribute equally to comfort until one becomes highly dominant [26]. The overall sensation seems to be dominated by the more annoying or stronger modality. Besides, Bellmann [6] concludes that there is a state of "balance" to be observed between vibration intensity and sound intensity, expected by drivers. Also, Leatherwood [123] showed that the contribution of each modality depends on their respective levels. But their interaction is clear: for vertical vibration levels which negatively affect the comfort, the addition of a sound has little influence. However, with a weak vibration level, the increasing of the noise level noticeably raises the discomfort assessment.

Moreover, the comfort issue is a scientific topic often treated in the transport domain (automotive and rail industries). Parizet et al. [26] and Howarth et al. [48] have two examples of this kind of study. Indeed, the first one realized an experiment in three stages: the discomfort's assessment of a sound stimulus alone, the discomfort's assessment of a vibro-acoustic stimulus and finally, global discomfort's evaluation of the vibro-acoustic stimulus. Results prove that vibrations have a small but significant influence on sound assessment. For some participants, the overall annoyance is only related to vibrations, while for others it seems to be linked to both modalities. In their study, Howarth et al. [48] focused on the discomfort evaluation caused by sounds and vibrations generated when a train passes close to a domicile. They conclude that vibrations do not affect the annoyance rating. Conversely, noise influences discomfort appraisal due to vibrations according to the relative magnitude of them. Therefore, discomfort caused by low vibrations decreases for higher noise levels and global discomfort is linked to relative levels of noise and vibration stimuli.

Finally, a last study, particularly interesting for our work, was realized by Amman et al. [219] on driving situations. The participants assessed the respective contribution of sound and vibrations (with six degrees of freedom) on driving situations (unsteady ones or passing on small obstacles) reproduced in a simulator. The experiment, linked to a preference issue, shows that the contribution of each modality is equivalent to the total preference evaluation of a driving situation.

As we have seen, the great diversity of studies conducted with sounds and vibrations makes it difficult to compare them. One can still conclude that a large amount of the research agrees that the global discomfort of a studied parameter depends on both modalities.

In the present study, we focus on vibrations' influence concerning the Dieselness issue. Indeed, a Diesel vehicle is one of many daily-life sound sources that each person may qualify according to their sensitivity. However, each person defines their own Diesel noise with their own feelings, which allows him to recognize it and often to disparage it. By using the Dieselness term, we want to refer to the "Diesel character": what in the stimuli (sound alone or sound and vibrations together) reminds participants of their experience with a Diesel car? Fastl et al. [20] [19] [44] define the Dieselness term as *"the typical sound character of Diesel engine"*.

Contrary to their definition we did not explain with an exact definition the Dieselness term to participants. The instructions for the experiment gave details only as the following (Appendix K): *Up to what point does this stimulus corresponds to a typical driving situation of a Diesel car? In other words, up to what point does it call up a Diesel stimulus? Up to what point does it allow you to be aware of a Diesel car?*. We let people keep their own definition of Diesel character[1].

This article presents results of the perceptual vibro-acoustic test on the Dieselness rating of six different driving situations of three various Diesel cars. It is made up of three parts. In the first part (Section 7.2), data recordings and processing (of sound and vibrations) are presented. Secondly, the experiment is detailed by precising the experimental setup and protocol (Section 7.3). Finally, results are presented and discussed taking into account the two populations (French and German). Indeed, previous marketing studies between these two countries have already been performed at Renault [28] [29]. Results highlight the differences between the two markets by distinguishing the driving style and the purchased vehicle type. Also, this study precises that French and Germans agree with their expectations about the vehicle and its engine. Through other studies about automotive noises, differences between Europe and Asia have been revealed by the scientific community [30] [31]. Our hypothesis about cultural differences is to not find big differences between the two populations (which represent the largest Diesel market in Europe).

7.2 Sound and vibrations database

7.2.1 Recording

Acoustics and vibro-acoustic data are recorded simultaneously. The equipment used is, respectively, a Head Acoustics system (HMS III dummy head) in the co-driver seat and a LMS device (Scadas SCM-05). To record vibrations, two three-axis accelerometers are used (x, y and z directions): one located on the steering wheel's hoop and the other one, on the left back side of the driver seat. Figure 7.1 shows the accelerometers' position. Two outputs of the dummy head and three channels of each accelerometer are linked to the eight

Figure 7.1: Locations of the three-axis accelerometers (blue) on the steering wheel (left side of the figure) and on seat (right side of the figure) during the vibrations' recordings.

inputs of LMS Scadas device. All records are realized in the same section of a test ring.

7.2.2 Processing

Different processes are applied to signals in order to prepare them for perceptual test:

1. all recordings are exported in to a wav format with a 44.100 kHz sampling frequency and 16 bit quantization;
2. vibration signals are filtered from 20 Hz to 150 Hz for the seat and from 20 Hz to 300 Hz for the steering wheel (see below);
3. all vibration signal are filtered with an inverse transfer function of the bench.

After resampling the sound and vibration data, the second treatment consists of filtering signals in two different frequency ranges. Two treatments steps were added for vibration preparation. First (step 4.), vibration signals

[1] In the following, we will use "Dieselness" or "Diesel character" terms to express the same idea.

were filtered from 20 Hz to 150 Hz for the seat and from 20 Hz to 300 Hz for the steering wheel. These choices were made for different reasons. We decided not to reproduce the accelerations below 20 Hz for two reasons. First, Figure 7.2 shows that - in the "worst" case for the 3-cylinder car which has the strongest vibration level - the accelerations are really weak and neglected below 20 Hz for the seat (at left) and for the steering wheel (at right). Secondly, below 20 Hz, physical disorders can appear (with resonances of stomach at 4-5 Hz, of liver at 4-8 Hz, of heart at 5-6 Hz and of kidney at 6-12 Hz) (Figure 3.6 in Chapter 3).

Finally, concerning the non-reproduction of the accelerations higher than 150 Hz, measurements of

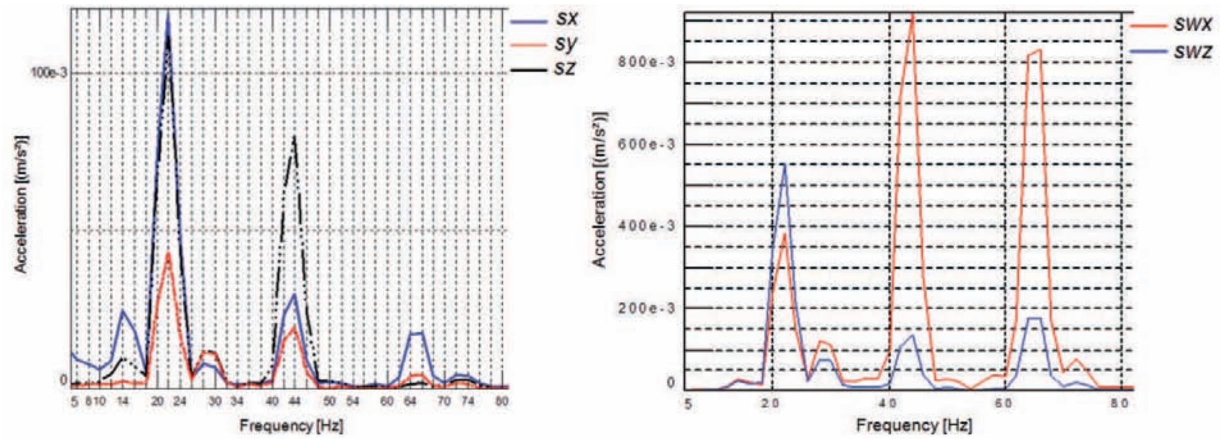


Figure 7.2: Frequency responses of the bench for a 3-cylinder car *hot idle* signal (Hyundai Getz). At left, the seat frequency response (x direction in blue, y in red and z in black) and at right, the steering wheel frequency response (x direction in red and z in blue).

electrodynamic exciters show two resonances. A first and most important one around 15 Hz which corresponds to rigid body mode, and a second, weaker one around 150 Hz due to moving parts (Figure 7.3). Moreover, weighting curves (Figure 7.4) indicate that sensitivity reduces above 150 Hz (for seat).

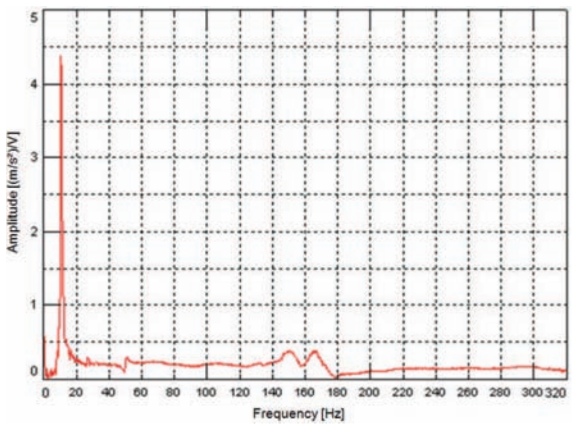


Figure 7.3: Transfer function of one electrodynamic exciter. Two resonances at 15 Hz and around 150 Hz are significant on all electrodynamic exciters.

By taking into account those three pieces of information, we limit the seat frequency range between 20 Hz and 150 Hz. Concerning the steering wheel, Barth [126] precised that it contributes strongly to the vibrations' perception especially beyond 100 Hz. In addition, Figure 3.6 which highlights theoretical resonance frequencies of different body parts, shows a sensitivity in a frequency range of 50-200 Hz for hands. Also, Giacomin and Ajovalasit [65] conclude that vibration energy can reach frequencies of up to 300 Hz and vibration modes with large resonant peaks appear for frequencies from 20 to 50 Hz. Therefore, filtering was made from 20 Hz to 300 Hz for the steering wheel's signals.

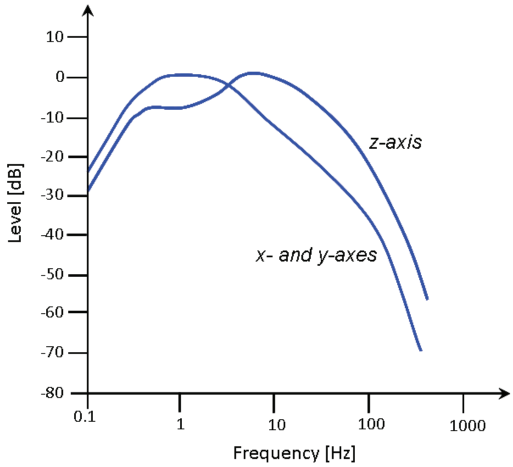


Figure 7.4: Weighting curves for seat sensitivity [9].

Finally to have a reproduction as faithful as possible to a vehicle's cabin, signals are filtered according to the bench behavior against vibrations' solicitations (cf 4.1.5.3). Indeed, the device's frequency response has to be the same as in real conditions. Therefore, we must minimize the bench's influence on signals that we want to reproduce. Measurements consist of several stages:

1. measurement of bench's frequency response to white noise, with three-axis accelerometers put in the same locations as in vehicle (for each direction): $H = Y.X^{-1}$;
2. calculation of the inverse frequency response: H^{-1},
3. verification of the flat frequency response of the bench after being filtered with a correction filter and a check with the original steady signals (measured in real conditions) reproduced with the bench: $X = H^{-1} . Y$.

Figure 7.5 illustrates through a synoptic diagram measurements of stages 1 and 3. No signal processing were

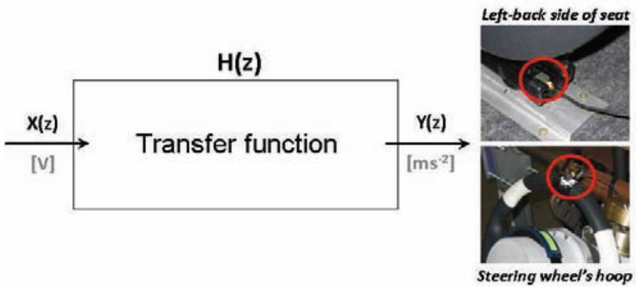


Figure 7.5: Synoptic diagram of measurements with picture of three-axis accelerometers on left-back side of seat (at the top) and in steering wheel's hoop (at the bottom).

applied to acoustic signals.

7.3 Experiment

Seventy-two stimuli were presented to participants (6 driving situations * 3 vehicles * 2 kinds of stimuli[2] * 2 repeats to check the reliability of the participants' answers). For each one participants made their Dieselness judgments on a Diesel continuous scale by taking into account the global stimulus.

This test was made up of two parts. The first one (named **orientation stage**) let the person immerse

[2] With and without vibrations.

themselves into the test conditions in order to understand the stimuli's basis. The second one (named **evaluation stage**) refers to the Dieselness evaluation for all stimuli, one by one. All stimuli were presented in random order. The instruction is presented in Appendix K.

The main goal of this experiment was to focus on vibrations' influence on Dieselness perception. As this experiment took place in two countries (France and Germany), a cross-cultural approach is highlighted in this article.

7.3.1 Participants

This experiment was performed in two countries: France and Germany. Thirty-five participants in each country took part in this experiment. For the recruitment participants had to meet some criteria. They must have not work in automobile or acoustic domains, to be a Diesel owner and use it regularly (daily or several times per week) and to be devoid of hearing problems (self report). Table 7.1 summarizes information (gender, mean age and anthropometric data like body-size or weight) about the seventy participants. The mean time duration needed by the participants for the whole test was 34 min for French and 39 min for German with standard deviations of 3.2 and 4.2 respectively.

As we can see, fourteen years separate the average age of French and this one of Germans. Let's

	Gender		**Mean**		
	Men	**Female**	**Age [yo]**	**Body-size [cm]**	**Weight [kg]**
French	21	14	43 (10)	172 (11)	75 (13)
German	26	9	29 (11)	178 (11)	80 (11)

Table 7.1: Anthropometric data - means and standard deviations in brackets - of French and German participants.

point out here that the recruitment of German participants was conducted among students of the University of Oldenburg. On the other hand the recruitment of French participants was achieved (as for all my experiences in France) by an external firm which chose the participants in order to have a representative sample of French diesel drivers.

7.3.2 Stimuli

Six different driving situations (from three different Diesel cars) were presented to participants: *hot idle*, *90-kph*, *start up the motor*, *stop the motor*, *acceleration* and *deceleration*. These driving situations were chosen in order to propose driving situations known and used in daily-life by all of the participants. The three different Diesel vehicles were a 3-cylinder in line (C1), a 4-cylinder in line (C2) and a 6-cylinder in a "V" (C3)[3]. For each driving situation, the two modalities, acoustics (A) only and vibro-acoustic (VA), were exposed to participants.

However, we notice here that lengths of all stimuli are different. They vary for instance from 2s for *start up the motor* and *stop the motor* to about 20s for *acceleration*. Indeed, during measurements on the test tracks, situations like *acceleration* or especially *traffic light start* can last 120s whereas situations like *start up the motor* or *stop the motor* last only around 3s. Obviously, we can not reduce *acceleration* or *deceleration* to 3s (or even less) and we can not extend the shorter ones. Therefore, we segmented the stimuli in different manners: for the steady ones (*hot idle* and *90-kph*), their length is the same (20s). Unsteady ones such as *start up the motor* and *stop the motor* last 2s. The differences in length are noticeable for others (*traffic light start*, *acceleration*, *deceleration* and *traffic jam*) but stimuli obtained did not exceed about 20s in order to base judgments on the engine revolution.

7.3.3 Apparatus

A simulation bench equipped with a car seat and a car steering wheel was used during experiments. It reproduced vibrations of three directions (x, y and z) for seat and the ones of two directions for steering wheel. Nevertheless, the two benches used for experiments did not reproduce the same directions for steering wheel.

[3] The three vehicles are the same as in Chapter 5: Hyundai Getz, Peugeot 308 and Renault Laguna Coupé, respectively.

Indeed, in France, x and z directions were reproduced whereas in Germany there were y and z.

For vibrations' reproduction, twelve electrodynamic exciters generated vibrations of the platform (four shakers for each direction) and two reproduced the steering wheel's ones (cf Figure 4.10 p 62 for the French bench). Sound stimuli were presented *via* a Head Acoustics system (HPS IV amplifier) and a Sennheiser half-opened electrostatic headphone. The whole system was driven by a computer equipped with a multi-channel sound card (RME Fireface 400). Each of the seven channels wav signals (sound stereo + three channels for seat + two channels for steering wheel) traveled through this sound card and Yamaha P7000S power amplifier system before the exciting platform and steering wheel. Stimuli reproduced through headphones and the vibratory bench corresponded to sensations that participants may experience when they are driving their car. No subwoofer was used to reproduce the low frequency.

7.3.4 Protocol

As precised in Section 7.1, the Dieselness question sums up as: *"Up to what point does this stimulus correspond to a typical driving situation of a Diesel car?*. The methodology chosen for Dieselness appraisal is a direct estimation on a continuous scale (Figure 7.6).

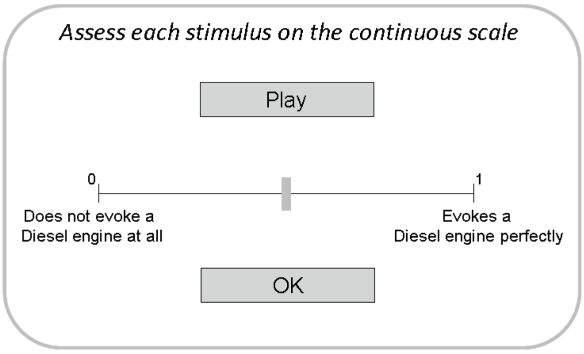


Figure 7.6: Example of the direct evaluation during the experiment (play the stimulus at the top, assess it in the scale at the middle and validate the choice with "OK" at the bottom).

Participants evaluate each signal with a cursor. They can move it from 0 ("the stimulus does not evoke a Diesel engine at all") to 1 ("the stimulus evokes a Diesel engine perfectly").

During the test, the same instruction was given to participants. They had to put their hands on the same place on the steering wheel (with markers on it) and they had to lay their feet down flat on the platform. At the end of the test, a small interview was carried out with each person in order to gather their impressions and sensations during the test and to obtain anthropometric data (Table 7.1 p 113). The instruction was translated in French (for the experiment in France) and in German (for the same experiment in Germany). These instructions can be consulted in Appendix K.

7.4 Results and discussion

Two groups of thirty-five participants performed the experiment in France and in Germany, respectively.

7.4.1 French participants

7.4.1.1 Reliability

The first step of analysis is to focus on the reliability of participants' evaluation. Indeed, during Dieselness rating, each stimulus was presented twice in a random order. Calculation of Pearson coefficient is made in order to examine the repetition factor. This coefficient allows to know that thirty-three participants are reliable in their evaluation. Indeed, the two participants who seem to be not reliable, obtain a correlation coefficient of 0.2 and 0.3. Therefore, results presented in following take into account only the thirty-three participants.

7.4.1.2 Results

In this section, mean scores of the six driving situations without vibrations (modality A) and with vibrations (modality VA) for all vehicles (3-cylinder car C1 in Figure 7.7, 4-cylinder car C2 in Figure 7.8 and 6-cylinder car C3 in Figure 7.9) are presented and discussed. A score of 0 corresponds to a *stimulus which does not evoke a Diesel engine at all* whereas a score of 1 represents a *stimulus which evokes a Diesel engine perfectly*. Each graph is divided into two parts with two stationary driving situations at the left side (*hot idle* and *90-kph*) and four unstationary ones (from *start up the motor* to *deceleration*) at the right side.

In addition, a repeated-measure analysis of variance with three within-subject factors (2 Modalities, 3 Vehicles and 6 driving Situations) was performed: P_{33} x M_2 x V_3 x S_6. The percentage of total variance

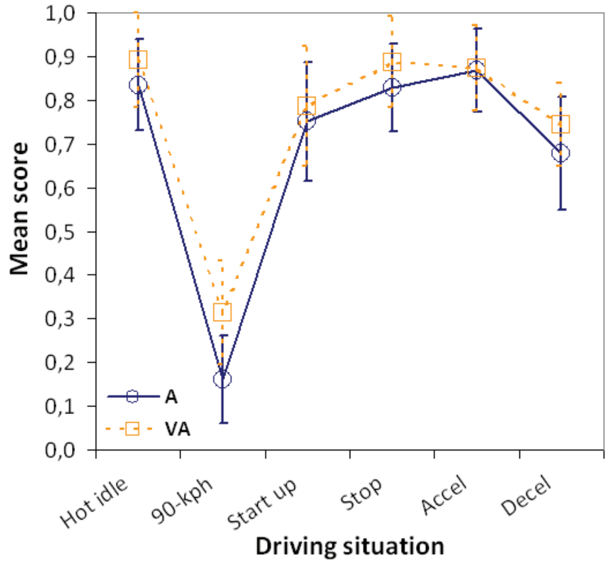


Figure 7.7: Dieselness mean scores and standard deviations of six driving situations for acoustics (A: blue round) and vibro-acoustic (VA: orange square) modalities for C1.

accounted for by each effect is indicated by the R^2 coefficient. All results of this statistical analysis are presented in Appendix L.

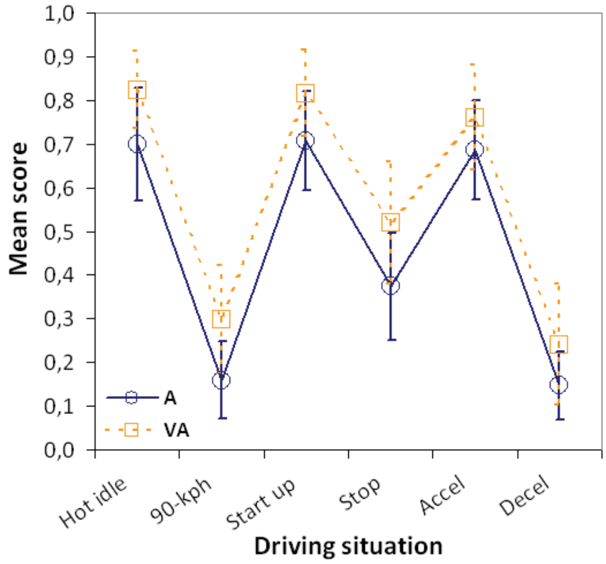


Figure 7.8: Dieselness mean scores and standard deviations obtained for C2.

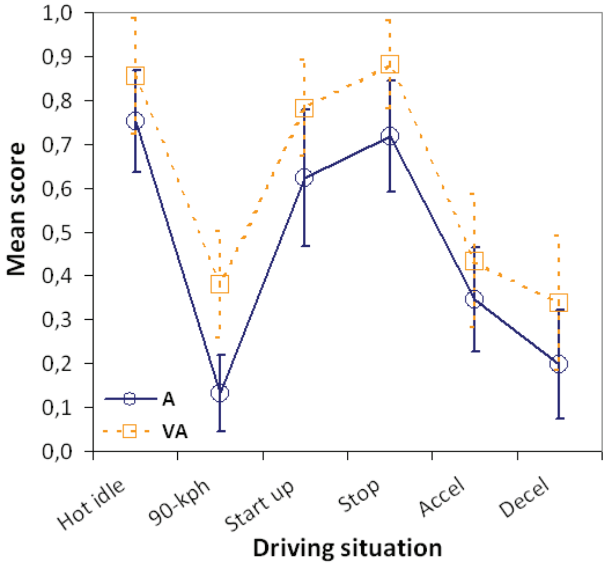


Figure 7.9: Dieselness mean scores and standard deviations obtained for C3.

Influence of the modality

By focusing on the charts (Figure 7.7 to Figure 7.9), the first observation concerns the fact that VA modality makes driving situations more Diesel than A modality. The variance analysis confirms this observation ($F(1, 32) = 44.10$, $p < 0.01$). However, this modality effect depends on the kind of vehicle ($F(2, 64) = 8.87$, $p < 0.01$). Indeed, by representing the interaction between modality and vehicle (Figure 7.10) which takes into account all driving situations, we notice that the vibration effect is more important for C2 and C3 than for C1. Moreover, the modality effect depends on the driving situation factor ($F(5, 160) = 3.58$, $p < 0.01$) too. For

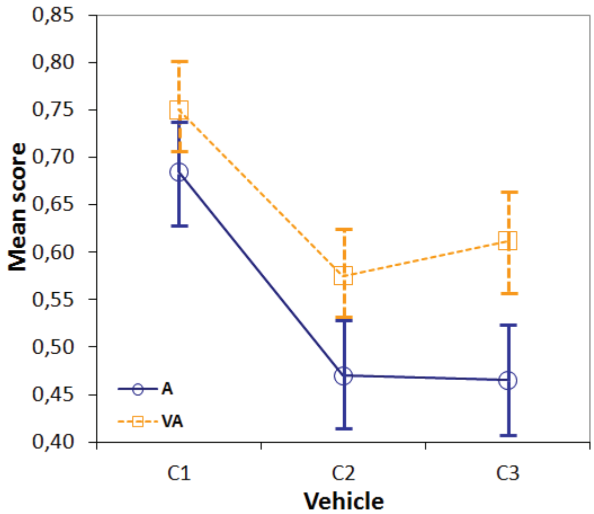


Figure 7.10: Variance analysis for the interaction between modality and vehicle for French.

example, we notice that for *acceleration* of a 3-cylinder car, this situation is felt as Diesel, with and without vibrations with a mean score of 0.87 (Figure 7.7). This particular result can be explained by the noise level of this driving situation. Indeed, this is the highest level with $L_{dB} = 110.96$ whereas for all other situations, L_{dB} is lower (Table 7.2 p 123). Moreover, since r.m.s. accelerations of seat and steering wheel (s_x, s_y, s_z, sw_x, sw_y, and sw_z in Table 7.2 p 123) are not the strongest for *acceleration*, their effects are reduced compared to those of other situations.

Influence of the vehicle

The charts also show different "behaviors" of Dieselness scores for C1, C2 and C3. This is confirmed with a significant effect of the vehicle factor ($F(2, 64) = 49.26$, $p < 0.01$). Indeed, by examining the different figures (Figure 7.7 to Figure 7.9), we can make some remarks. We notice that C1 and C3 obtain mean scores very close for *start up the motor* (respectively 0.79 and 0.78) and *stop the motor* (respectively 0.89 and 0.88), for VA modality. If one refers to Table 7.2 p 123, one can point out that even if the sound level of C1 is higher (except for *acceleration* and *deceleration*) than those of C3, the r.m.s. acceleration of the steering wheel appears higher for C3 than for C1. Morioka and Griffin [120] compared the perception thresholds of fore-and-aft, lateral and vertical vibrations by seated persons (at the hand, the foot and the seat) in 2008. Their results show that perception threshold at the hands is about 0.04-0.06 ms^{-2} r.m.s. Besides, Table 7.2 p 123 presents metrics higher than this threshold. Therefore, we can suggest that, of course, accelerations play a key role for the Dieselness evaluation of C3. The last observation concerns the steady driving situations *hot idle* and *90-kph* for which a contrast analysis was performed. This analysis reveals that there is no difference between *hot idle* of C1 and C3. We find the same results for *90-kph*. This analysis shows that the distinction between a 3-cylinder car and a 6-cylinder is not very clear according to certain driving situations. We can bring another explanation for difficulties to distinguish C1 and C3 that those two vehicles have common odd engine harmonics. Figures 7.11 and 7.12 present spectrograms of accelerations for a 3-cylinder car in line and 6-cylinder car in a "V". We precise on figures, their main odd engine harmonics (in green, above the harmonic that the number describes, at right side). These two spectrograms show a fairly close spectral analysis with, more particularly, harmonics 1.5 and 3.

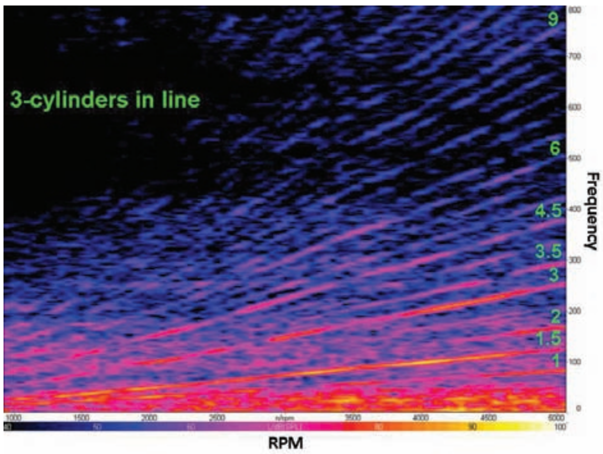


Figure 7.11: Acceleration: spectrogram of 3-cylinder car in line.

Influence of the driving situation

Concerning the six driving situations, the graphics well present the differences between the six ones and the ANOVA analysis confirms its significant effect on Dieselness evaluation with $F(5, 160) = 87.55$, $p < 0.01$. Moreover, the calculation of R^2 reveals that this factor has the strongest effect ($R^2 = 34.7$ in Table 8.15 in Appendix L).

If we focus on interactions between driving situation and vehicle for which the effect of interaction is strong ($R^2 = 10.8$), we can conclude that the vehicle's impact on Dieselness assessment depends on the situation. Indeed, Figure 7.7 to Figure 7.9 show that Dieselness of *90-kph* situation is different from Dieselness of other driving situations for C1, which is not the case for C2 and C3. For those last two vehicles, *90-kph* and *deceleration* are not different anymore. The *deceleration* has the distinction of being little Diesel and even less Diesel than certain stationary situations. Indeed, during this driving situation, the combustion noise (typical of the sound of Diesel) is not involved. By listening to recordings, it is possible to explain the difference between the 3-cylinder car with the two others. *Deceleration* of C1 (3 cylinders) is characterized by the presence of booming noise (as Diesel clatter with low frequencies). It thus differs from *90-kph* which contains high frequency wind

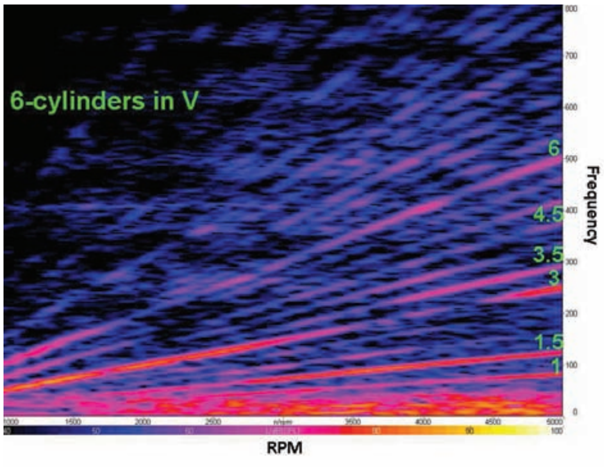


Figure 7.12: Acceleration: spectrogram of 6-cylinder car in "V".

noise that hides the typical noise of the Diesel engine. The *deceleration* of the two other vehicles are closer to *90-kph* than others.

7.4.1.3 Comparison between two sound experiments

The previous results, which have been presented, concern an experiment constituted of acoustic stimuli and of the same vibroacoustic stimuli. And we discussed the results obtained by separating the assessment of Diesel character for the acoustic stimuli and the same evaluation for the vibroacoustic stimuli. It is therefore interesting to compare here the results about the sound experiment on the Diesel character's perception of twelve driving situations discussed in Chapter 5 and the results discussed in this chapter concerning the acoustic and vibroacoustic experiment of six driving situations. Here, we will only compare the results of the French participants.

Both sound experiments presented in Chapter 5 and in this chapter used the same experimental protocol. Indeed, the two test instructions are very similar (Appendix D and Appendix K). The Diesel character was evaluated on a continuous scale from 0 to 1. The sound reproduction was made by the same headphones (paragraph 7.3.3). However, two main differences exist:

- the first experiment (Chapter 5) was used to assess twelve different driving situations (six steady and six unsteady) while the second experiment (Chapter 7) was concerned with the appraisal of six driving situations, already proposed in the first experiment (two steady and four unsteady);
- the second experiment provided both acoustic stimuli and vibroacoustic stimuli.

Figure 7.13 presents the results of three specific driving situations: *stop the motor*, *acceleration* and *hot idle* for the three vehicles C1 (3-cylinder car in line), C2 (4-cylinder car in line) and C3 (6-cylinder car in "V"). It allows me to compare the Dieselness assessment of the sound stimuli of experiment $n°1$ (full blue diamond), of experiment $n°2$ (open blue diamond) and the vibroacoustic stimuli of experiment $n°2$ (full orange square).

In the case of C1, the Diesel character of sound stimuli was roughly judged equivalent in the case of the two unsteady situations (*stop the motor* and *acceleration*). Apart from these two cases, the results for sound stimuli show some disparity. In the case of the two unsteady situations, the difference between the two experiments can even go from a difference of 0.06 to 0.38. The main reason that can explain this difference lies in the stimuli corpus chosen. Indeed, the experiment $n°2$ that mixes both acoustic and vibroacoustic stimuli has a main effect: minimizing the Dieselness perception of acoustic stimuli especially for vehicles C2 and C3 (4-cylinder and 6-cylinder cars). We see that in every case of C1, the Dieselness perception in the two experiments leads to two similar assessments (taking into account only the sound stimuli). It is therefore understandable that in this case of vehicle, vibrations do not affect the Diesel assessment. Also, the corpus of acoustic and vibroacoustic stimuli of the experiment $n°2$ had no effect on the appraisal. However, the other two vehicles that have a noise level below that of C1 (Table 7.2), the sound stimuli mixed with some vibrational stimuli are judged very little Diesel. So, that is the noise component which bears the Diesel character.

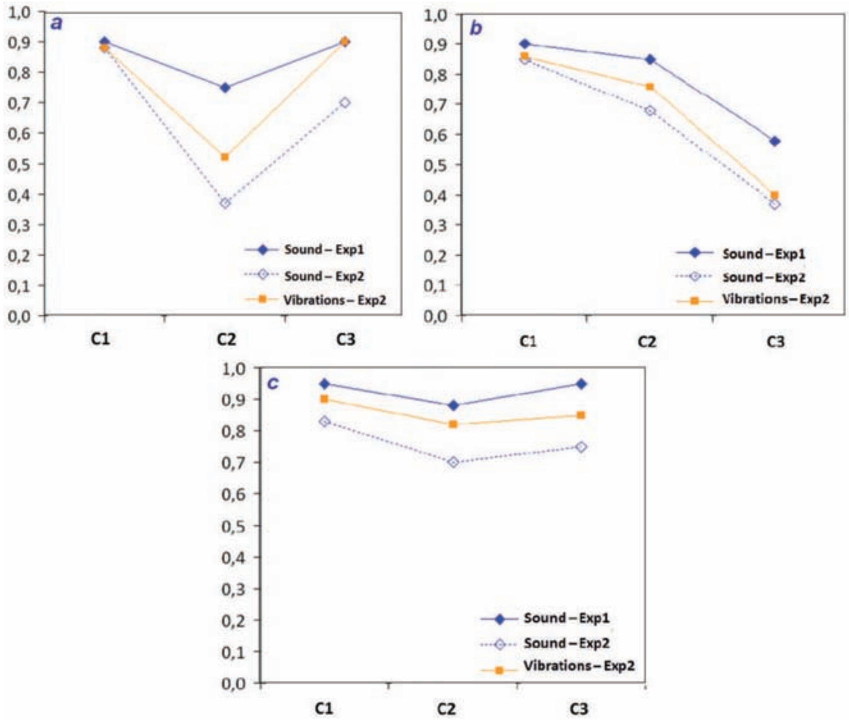


Figure 7.13: Dieselness mean scores obtained for C1, C2 and C3 for sound stimuli of experiment $n°1$ (Chapter 5) in full blue diamond, for sound stimuli of experiment $n°2$ (Chapter 7) in open blue diamond and for stimuli with vibrations of experiment $n°2$ (Chapter 5) in full orange square. The figure presents three particular cases: (a) *stop the motor*, (b) *acceleration* and (c) *hot idle*.

7.4.2 German participants

For this population, the analyses were performed in the same manner as for French results.

7.4.2.1 Reliability

Calculation of Pearson coefficient shows thirty-four participants reliable in their evaluation. Indeed, only, one participant obtains a coefficient of 0.3 which does not represent a strong correlation between his two evaluations. Therefore, results presented in the following take those thirty-four participants with reliable evaluations into account.

7.4.2.2 Results

Following charts present mean scores obtained for German participants. Driving situations (on the abscissa) are presented in the same order as for French results (from stationary to unstationary ones). In addition, a repeated-measure analysis of variance with three within-subject factors (2 Modalities, 3 Vehicles and 6 driving Situations) was performed: P_{34} x M_2 x V_3 x S_6. All results of this statistical analysis are presented in Appendix L.

Influence of the modality

Same conclusions as for French can be deduced here. With vibrations, signals are felt more Diesel than without (Figure 7.14 to Figure 7.16).

Indeed, the variance analysis confirms this observation ($F(1, 33) = 13.00$, $p < 0.01$). However, some exceptions appear: *stop the motor* for C1 with 0.86, *hot idle* for C2 with 0.72 and *start up the motor* and *stop the motor* for C3 with 0.70 and 0.77 obtain same main scores for both modalities (A and VA). Indeed, this dependency of driving situation is confirmed by the analysis of variance ($F(5, 165) = 2.51$, $p < 0.05$). However,

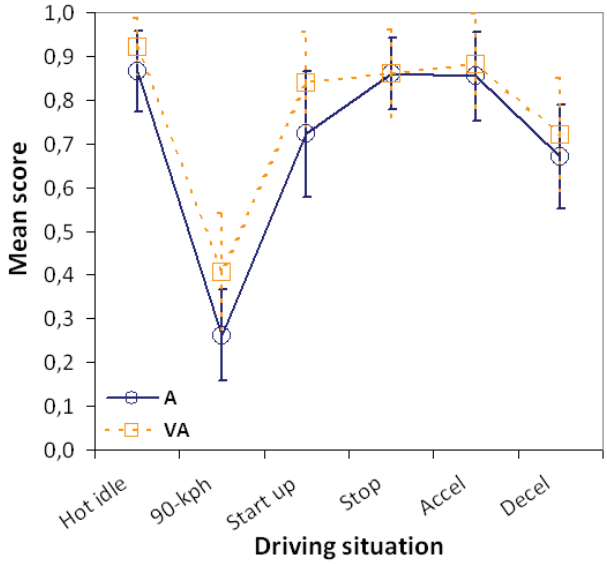


Figure 7.14: Dieselness mean scores and standard deviations of six driving situations for acoustics (A: blue round) and vibro-acoustic (VA: orange square) modalities for C1.

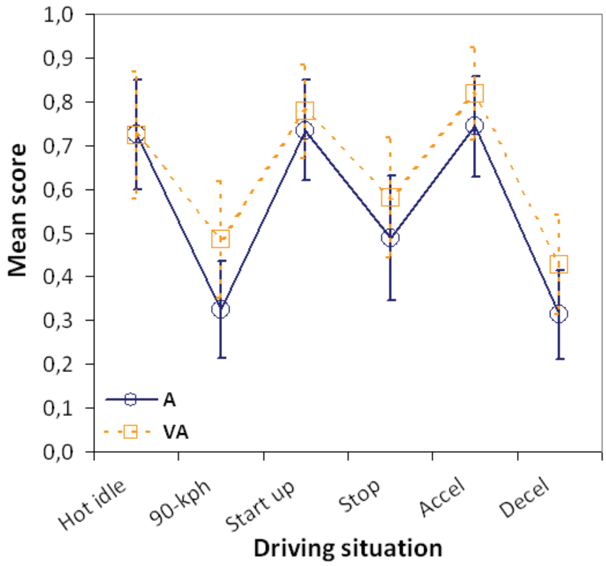


Figure 7.15: Dieselness mean scores and standard deviations obtained for C2.

contrary to French results, there is no longer a dependency between modality and vehicle (Figure 7.17). The results show less differences between A and VA modalities than for French participants and are not the same all over. Its effect is practically equivalent for C1, C2 and C3.

Influence of the vehicle

In order to compare vehicles between them, let's refer to Figures 7.14, 7.15 and 7.16. Indeed, the charts show an influence of vehicle with different Dieselness scores for C1, C2 and C3 which is confirmed with a significant effect of this factor ($F(2, 66) = 39.69$, $p < 0.01$). As for French results, C1 appears as being more Diesel than other vehicles for both modalities. Concerning the interaction between modality and vehicle, there is little or even no influence on Dieselness appraisal (cf Table 8.16). The last observation concerns the steady driving situations *hot idle* and *90-kph* for which a contrast analysis was performed. This analysis reveals that there is a significant difference between *hot idle* of C1 and C3 ($p < 0.05$) and a very significant difference

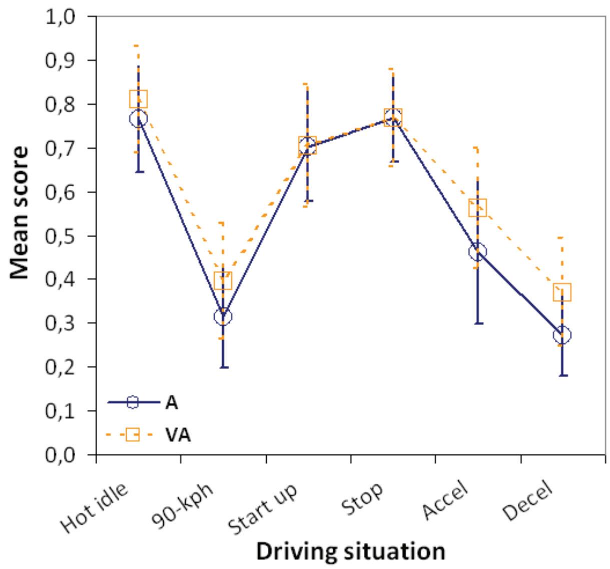


Figure 7.16: Dieselness mean scores and standard deviations obtained for C3.

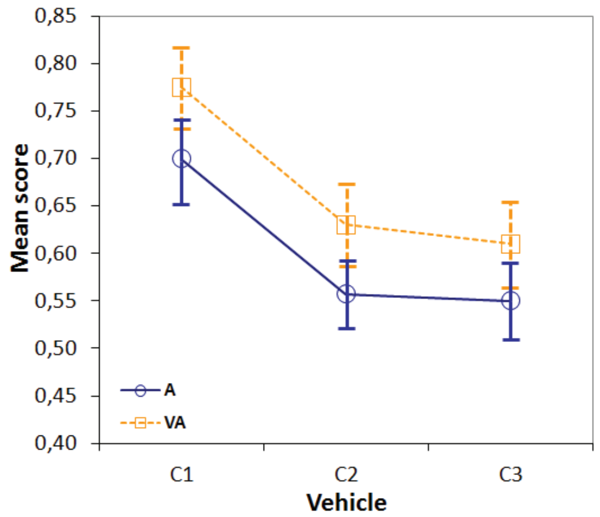


Figure 7.17: Variance analysis for the interaction between modality and vehicle for Germans.

between C1/C3 and C2 ($p < 0.01$). Results obtained for *90-kph* are totally not significant.

Influence of the driving situation

Concerning the situations, the figures present the differences which exist between them, and the ANOVA analysis confirms its significant effect on Dieselness evaluation with $F(5, 165) = 56.89$, $p < 0.01$ and with the strongest effect (R^2=27.4 compared to 1.2 and 5.5 for respectively modality and vehicle factors).

If we focus on interactions between driving situation and vehicle for which the effect of interaction is the strongest (R^2=7.7), we can conclude that the vehicle's impact on Dieselness assessment depends on the situation for German too. Indeed, Figure 7.14 to Figure 7.16 show that for C1, Dieselness of *90-kph* situation is different from Dieselness of other driving situations for C1 (but no longer for C2 and C3 as found for French participants).

In order to conclude, we can notice that all of the effects (modality one by one or interactions between them) are really lower than for the French participants.

7.4.3 Cultural influence on Dieselness assessment

A mixed-model design ANOVA with one between-subjects variable (all participants) and three within-subjects variables was performed: S(P) x M_2 x V_3 x S_6. Appendix L presents results of this ANOVA analysis.

This analysis shows that the main factors (Modality, Vehicle and Situation) have a significant effect on Dieselness evaluation whereas the participants do not have one. Concerning the interactions which take into account both populations, none of the interactions gives significant results except interactions between modality, vehicle and participants (M x V x P with $F(2, 130) = 5.62$, $p < 0.01$. Let's see on Figure 7.18 in order to focus on this particular interaction.

It presents results for each car C1, C2 and C3 for each group of participants (French at left side and

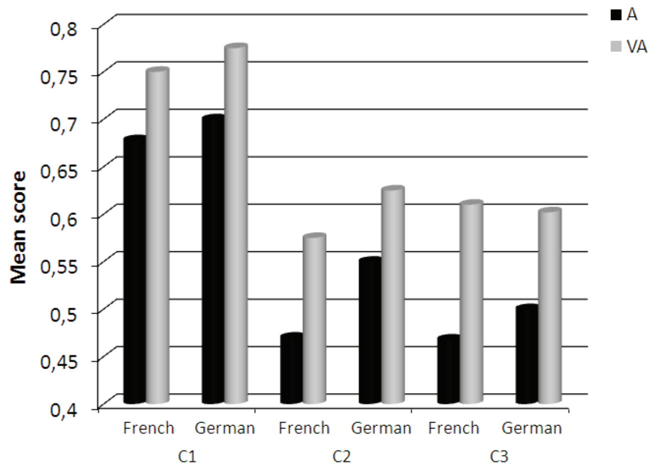


Figure 7.18: Mean scores for all driving situations taken together for each car (C1, C2 and C3), for each population (French and German) and for A and VA modalities (respectively in black and grey).

German at right side of each column). Scores are given for the whole of the driving situations (because M x S x V x P has no significant effect with $F(10, 650) = 1.74$, $p > 0.01$). Therefore, each chart's bar shows score for one vehicle, one population and one modality but for the six driving situations. We can conclude that:

- the modality factor has an effect ($F(1, 1) = 48.97$, $p < 0.01$). With vibrations, Dieselness scores are higher than without;
- the kind of vehicle has an effect too ($F(2, 2) = 88.41$, $p < 0.01$),
- the group of participants has an effect with particularities according to some parameters. Indeed, for C1, French and Germans evaluate A and VA modalities in a same manner. For C2, they do not agree with Dieselness score but differences between A and VA are similar. Finally, the two populations are distinguished for C3. The big difference concerns stimuli with vibrations (VA modality). Even if they do not assess acoustic stimuli in the same way, Dieselness scores are really close for stimuli with vibrations (respectively for French and German, 0.61 and 0.60).

This last result confirms a previous remark for C3 that noise level plays an important role on Dieselness assessment. The adding of vibrations do not allow to distinguish the populations.

7.4.4 Principal component analysis

In order to explain some results' tendencies, a principal component analysis (PCA) was performed with all stimuli (6 driving situations x 3 vehicles). Two metrics were calculated for each stimulus: RMS value of acceleration $[ms^{-2}]$ of three directions of seat (s_x, s_y and s_z) and of steering wheel (sw_x, sw_y and sw_z) and sound level L_{dB}. Table 7.2 presents those descriptors.

Vehicle	Situation	s_x	s_y	s_z	sw_x	sw_y	sw_z	L_{dB}
C1	Hot idle	0.08	0.10	0.11	0.49	0.46	0.42	102.45
	90-kph	0.04	0.04	0.05	0.45	0.22	0.36	107.61
	Start up	0.01	0.03	0.02	0.20	0.12	0.13	103.03
	Stop	0.07	0.08	0.10	0.44	0.26	0.35	98.89
	Acceleration	0.03	0.03	0.02	0.48	0.18	0.28	110.96
	Deceleration	0.03	0.03	0.03	0.41	0.18	0.32	109.79
C2	Hot idle	0.1	0.07	0.05	0.68	0.47	0.55	92.29
	90-kph	0.02	0.03	0.03	0.56	0.40	0.40	105.74
	Start up	0.03	0.05	0.04	0.54	0.27	0.4	96.83
	Stop	0.03	0.04	0.04	0.38	0.34	0.35	89.10
	Acceleration	0.03	0.02	0.02	0.59	0.27	0.41	107.42
	Deceleration	0.04	0.03	0.03	0.41	0.31	0.33	104.61
C3	Hot idle	0.07	0.07	0.14	0.70	0.28	0.45	97.40
	90-kph	0.03	0.02	0.04	0.94	0.24	0.48	106.22
	Start up	0.03	0.03	0.03	0.28	0.12	0.19	95.18
	Stop	0.05	0.06	0.10	0.60	0.35	0.48	92.84
	Acceleration	0.03	0.03	0.03	0.49	0.16	0.33	107.38
	Deceleration	0.02	0.02	0.02	0.59	0.19	0.38	104.41

Table 7.2: Metrics' table for six driving situations and three vehicles (C1: 3-cylinder car, C2: 4-cylinder car and C3: 6-cylinder car).

Thanks to the correlation matrix, different results can be done. Indeed, a strong correlation exists between s_x, s_y and s_z with correlation values from 0.714 to 0.856. sw_x is correlated with none of the other parameters except with sw_z. This conclusion confirms that level of those two directions are close and distinguishes from sw_y. Finally, there is no correlation between L_{dB} and other vibration parameters. Those first conclusions are confirmed with representation of the descriptors after extraction. Besides, Table 7.3 presents the quality of representation for each of them. All descriptors are well represented (except sw_y and L_{dB}). After this extraction step, two factors account for 78% of the variance (with only 57% of variance represented by the first one). Table 7.4 presents the rotated factor matrix of this analysis. This table allows us to see that Factor 1

	Initial	Extraction
s_x	1.000	0.826
s_y	1.000	0.909
s_z	1.000	0.724
sw_x	1.000	0.909
sw_y	1.000	0.681
sw_z	1.000	0.962
L_{dB}	1.000	0.478

Table 7.3: Quality of descriptors' representation after extraction.

represents s_x, s_y and s_z whereas Factor 2 represents sw_x and sw_z. sw_y and L_{dB} are not represented with these two factors.

Finally, Figure 7.19 p 125 presents a projection on the 2D space of each situation for each vehicle. We can find the six different driving situations assessed by participants: in black round, 3-cylinder car (C1), in red triangle, 4-cylinder car (C2) and in green cross, 6-cylinder car (C3). This representation allows us to isolate groups whose behavior seems similar along the chosen factors. We can note some groups of situations. Indeed, the three *hot idle* seems to be together with Factor 1 which discrimates them from other situations. Referring to Table 7.2, we can see that metrics s_x, s_y and s_z of *hot idle*, are closely coupled for all Diesel cars. *90-kph* of C3 is isolated from all other situations. It is discriminated along Factor 2 (represented by sw_x and sw_z). This situation which seems to be not Diesel for all participants, can differentiate three vehicles thanks to sw_x (with

	Factors	
	Factor 1	**Factor 2**
s_x	0.827	0.377
s_y	0.946	0.123
s_z	0.819	0.231
sw_x	-0.051	0.952
sw_y	0.598	0.568
sw_z	0.318	0.928
L_{dB}	-0.690	0.051

Table 7.4: Rotated factor matrix: values which represent weight of a descriptor on the factor..

0.45, 0.56 and 0.94 ms^2 for C1, C2 and C3, respectively). Concerning unsteady situations, differences are less obvious. First, for the 4-cylinder car (red triangles), almost all situations are concentrated at the middle of Figure 7.19. Factors 1 and 2 do not discriminate situations between them. *Start up the motor* and *stop the motor* are discriminated along Factor 1 for C1 and C3. More precisely, *start up the motor* and *stop the motor* are really different along this axis but fairly similar between C1 and C3 (see metrics of Table 7.2). Whatever the car, *acceleration* and *deceleration* are close.

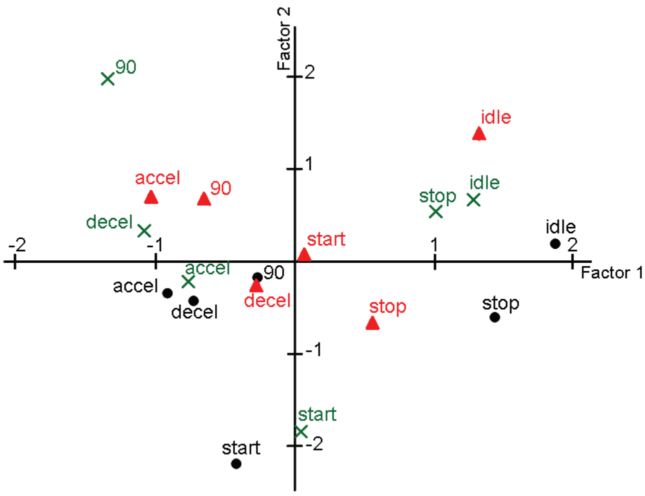


Figure 7.19: Representation of PCA analysis with the first two factors (black rounds for C1, red ones for C2 and green ones for C3).

This study deals with interaction between acoustics and vibrations concerning the following question: is there any influence of additional vibrations on Dieselness assessment, *i.e.* Diesel engine cars' character? Dieselness of six different driving situations of three various types of Diesel cars was rated by thirty-five participants during a perceptual vibro-acoustic experiment. This test was performed in France and in Germany. Thirty-six stimuli were assessed on a Dieselness scale. Indeed, participants had to evaluate each stimulus (only sound or sound and vibrations) along a continuous scale from 0 to 1.

Results show similar tendencies for French and German. First of all, vibrations lead to slightly higher evaluations and statistical analyses highlight its influence on Dieselness evaluation but with a weak impact on it. In addition, vibrations' effect depends on different parameters: kind of Diesel cars (3-, 4- or 6-cylinder car) and driving situation too. Despite a few differences, French and Germans totally agree with the fact that *hot idle* is the most Diesel driving situation, whatever the modality and whatever the vehicle [43].

PCA analysis allowed us to detect two main factors which distinguishes the different driving situations of the three Diesel cars. Those two factors correspond to five metrics of vibrations. The first group together three seat metrics while the second one is represented by sw_x and sw_z. They contribute to distinguishing *90-kph*, *acceleration* and *deceleration* between all vehicles.

All results have to be taken with caution because we refer to one 3-cylinder, one 4-cylinder and one 6-cylinder car. Therefore, it seemed difficult to generalize for all vehicles of lower, middle and upper classification, respectively. This study provides at least an idea of the differences between three types of engines.

Currently, economical and environmental policies urge car manufacturers toward downsizing, *i.e.* a reduction of the cylinder number. If we focus on the 3-cylinder car of this experiment, we notice that it is appraised as the most Diesel between three vehicles. Nonetheless, vibrations' contribution is not significant because with sound only, this car is already assessed as a strong Diesel (contrary to the two other vehicles). Despite those remarks, it is surprising that the three vehicles are not clearly distinguishable between them. Even, 3- and 6-cylinder ones are rated in a similar manner. We have deduced that similarity between them can be explained by their close spectral structure and noise level. Distinction between vehicles is sharper on the *acceleration* and *deceleration* situations.

Chapter 8

Vibroacoustic space of Diesel

As we have seen in the previous chapter, vibrations lead to slightly higher Dieselness evaluations, but statistical analyses highlight its weak influence on them. In addition, vibrations' effect depends on different parameters such as type of Diesel car with three, four or six cylinders.

In order to pursue the features of the Diesel vehicle, we are interested in the vibrations' influence on the revealed sound space of Chapter 6. So, after having defined the driving situations, which best represent the typical sound of Diesel vehicles in Chapter 5 and the sound spaces which characterize them in Chapter 6, we pursued with the introduction of vibrations in order to determine the Diesel vibroacoustic space. However, this chapter presents the multidimensional approach for only one driving situation: the *acceleration*. Indeed, for some reasons of feasibility, we have ignored the *hot idle* situation for this last experiment. This will be exposed in paragraph 8.1.2.

This chapter is made up of two sections in which one first presents the multimodal experiment before discussing the results by comparing them with those of Chapter 6.

8.1 Experiment

Chapter 6 presented the perceptual sound spaces of *hot idle* and *acceleration* by explaining the different dimensions of each one. After the study of the vibrations' influence on Dieselness evaluation in Chapter 7, we reiterate a vibroacoustic experiment on perceptual space this time. Is there an influence of vibrations on the perceptual Diesel sound space?

8.1.1 Participants

Forty-nine participants performed this vibroacoustic test. For the recruitment, participants had to correspond to the same criteria as for all other experiments of this thesis work: they should not have worked in automobile or acoustics domains, to be a Diesel owner and use it regularly (daily or several times per week) and to be devoid of hearing problems (even if this criterion has not been checked). Table 8.1 summarizes information about these participants.

Men	**Female**	**Age [yo]**
25	24	43 (11)

Table 8.1: Data about participants of vibroacoustic experiment: number of men, of female, mean age and standard deviations in brackets.

8.1.2 Stimuli

Stimuli correspond to the same ones which have been presented to the group of forty-one persons in the listening test (cf paragraph 6.2.2 of Chapter 6): *acceleration*. However, the purpose of this experiment is to have a multimodal approach. Therefore, sound stimuli are presented simultaneously with five degrees of freedom of vibrations (s_x, s_y, s_z, sw_x and sw_z[1]). In the same manner as for the *acceleration* stimuli of the listening test, fifteen stimuli are presented to the participants. No acoustic treatment was made and vibrations were reproduced similar to treatments detailed in Chapter 4.

The choice of keeping only *acceleration* was made for different reasons. As it is known for limiting the bias in an experiment, different parameters as duration or loudness must be fixed. Indeed, concerning the *hot idle*, the two parameters are easy to fix. However, by introducing the vibrations, some difficulties appeared. How to present equal level vibrations for the different stimuli without changing the ratio between sound and vibration? As the sound stimuli was equal in loudness and we want to compare acoustic and vibroacoustic experiments, it appeared to be difficult to keep this fixed "loudness". However, the *acceleration* driving situation was not fixed in duration or in loudness. Therefore, it was easier to add vibrations to it.

Even if the first remarks concern feasability reasons, the choice of *acceleration* seems important: the contribution of my work for a new approach. As we have already precised, *hot idle* is consistently studied in the scientific community. Moreover, in order to get closer to a *positive* approach, the *acceleration* appears to be a good candidate notably by the fact that several studies, which focus on gasoline cars through the sportivity idea, were performed on *acceleration*.

8.1.3 Apparatus

The experiment was performed in the same soundproof booth at Renault with the same Sennheiser half-opened electrostatic headphone (Chapter 4) and with the same subwoofer as for the listening test (Chapter 6). Moreover, the participants were settled on the same bench described in paragraph 4.1.5.2 of Chapter 4.

8.1.4 Protocol

The test's protocol is exactly the same as the one detailed in Chapter 6. The reader will be able to refer to paragraph 6.2.4 for the precise description. The instruction is presented in Appendix M.

[1] This notation has already been used in Chapter 7 with s for seat and sw for steering wheel.

8.2 Vibroacoustic space of Diesel: multimodal approach

The following of this chapter consists of focusing on the vibroacoustic space of the *acceleration* driving situation. The data consist of a vector of 105 paired comparisons for 15 different *accelerations*. The steps of the analyses are exactly the same as in Chapter 6.

8.2.1 Cluster analysis

The hierarchical cluster analysis which is performed on the forty-nine participants shows that five participants are uncorrelated with the others. Indeed, by focusing on their evaluations, one of them used the scale only between 0.49 and 0.51. Concerning the four others, they used it only between 0 and 0.5. Therefore, the multidimensional analysis is performed on forty-four reliable participants.

8.2.2 Multidimensional analysis

In order to obtain the multidimensional representation of vibroacoustic stimuli, the *CLASCAL* model with its different steps of analysis is used. In this case, the results give three latent classes (with respectively 19, 9 and 16 participants) and two dimensions for the case with specificity. Table 8.2 presents the log likelihood and BIC values for spatial model with three latent classes from one to six dimensions. For this selected spatial model, through *CLASCAL* model we obtain the coordinates of each stimulus along each common dimension (Figure 8.1), the specificity value for each stimulus and the weight of each latent class for each dimension (Table 8.3).

	Without specificities		**With specificities**	
Dimension	**logL**	**BIC**	**logL**	**BIC**
1	-693	1545	1095	-1887
2	138	20	1203	-1967
3	650	-870	1152	-1730
4	872	-1179	1078	-1447
5	1011	-1321	1065	-1286
6	1070	-1303	1220	-1461

Table 8.2: Vibroacoustic experiment on *acceleration*: Log likelihood and BIC values for spatial model of three latent classes for 44 participants and 15 vibroacoustic stimuli.

	Number of dimension	
Latent class	**1**	**2**
Class 1	0.92	0.68
Class 2	0.92	1.28
Class 3	1.15	1.04

Table 8.3: Vibroacoustic experiment on *acceleration*: Estimated weights in the selected two-dimensional model with specificities for three latent classes.

However, by plotting the different spaces corresponding to each latent class with their own weight on each dimension, we noticed that the three spaces are really close to the average space (*i.e.* the one which take into account all participants). This spatial configuration is shown in the two-dimensional projections in Figure 6.2. However, the three other perceptual spaces are presented in Appendix N.

The three latent classes give close vibroacoustic space. Therefore, we present the class which has the stronger effect (with the highest weight) on the two dimensions (circle on Figure 8.1). The repartition of stimuli on the space is close to the one on the space of Figure 6.2. Only the gasoline cars ($n°13$ and 15) are perceived differently from the others but still are similar between themselves. This result shows that in this acceleration case people can distinguish Diesel from gasoline vehicles. This difference may be found in the sporty character of gasoline ones. Concerning the 3-cylinder cars $n°2$, 6 and 7, the group is split. The sound of VW Polo ($n°6$)

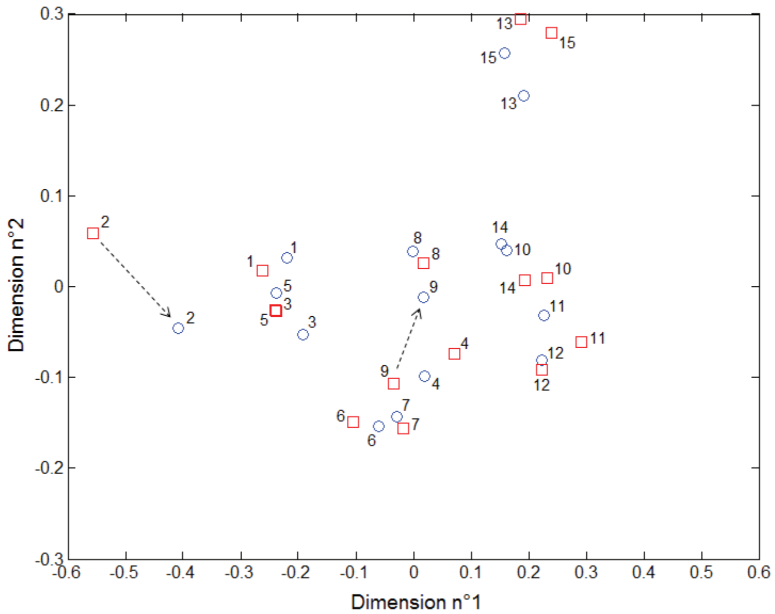


Figure 8.1: Representation of the perceptual space obtained by the *CLASCAL* analysis for *acceleration* with *acoustic* stimuli (square) for the 22 participants of the 3^{rd} latent class and *vibroacoustic* ones (circle) for the 19 participants of the 1^{st} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

and of Hyundai I10 ($n°7$) seem to be close to the majority of the sound corpus. Dimension $n°1$ explains the difference between Hyundai Getz ($n°2$) from all others whereas dimension $n°2$ explains the distance between Diesel and gasoline cars. Concerning the influence of subwoofer, still here, there is no big difference between $n°11$ and 12.

In addition, Figure 8.1 presents at the same time the acoustic space (red squares) and the vibroacoustic one (blue circles). As we will see, the two dimensions of the spaces are not explained by the same parameters. However, even if we can conclude that the reasoning is not totally scientific, the superposition of the two spaces allows us to conclude about some interesting behavior. The main remark is that there is no significant difference between the acoustic space (square) and the vibroacoustic one (circle). This result joins the conclusion of Chapter 7 about the weak influence of vibrations on the Dieselness evaluation. Still here, the results obtained with and without vibrations are really similar. However, the two cases precised with the arrows on Figure 8.1 prove the contrary. Indeed, with vibrations Hyundai Getz ($n°2$) appears to be less different from the rest of stimuli, and Mercedes MC220 ($n°9$) moves along the dimension $n°2$. Finally, as for the listening test (Chapter 6), the modeling of the space without gasoline stimuli $n°13$ and 15 reveals a difference along the second dimension but with the same coordinates along the first one. Concerning the influence of the subwoofer, still here, there is no big difference between $n°11$ and 12.

To conclude, it would be wiser to make a Mantel test. This test is used for the correlation calculation between a two dissimilarity matrix. It allows us to measure the correlation between two matrices typically containing measures of distance. It is one way of testing for spatial autocorrelation even if they are explained by different parameters (which is the case here).

Acoustic analyses

As we have seen just before, the acoustic space and the vibroacoustic one of *acceleration* are not really different especially along the dimension $n°1$. In the same way as for the perceptual acoustic space, acoustic and psychoacoustic features are calculated. Moreover, values such as r.m.s.[2] and maximum levels of the seat and of the steering wheel[3] are calculated too. We focus on the space with 15 stimuli. The same three parameters N5, N10 and STLmax, which explain the dimension $n°1$ of *acceleration* sound space in Chapter 6, correlate well here too. The correlation coefficients are -0.91, -0.92 and -0.91, respectively. Indeed, as the vibroacoustic stimuli maintained the same loudness as the sound ones and that both sound and vibroacoustic spaces are really close, it is normal to observe the same correlation between the unstationary loudness and the dimension $n°1$. Figure 8.2 presents the linear regression between the first dimension and the three unstationary loudness N5

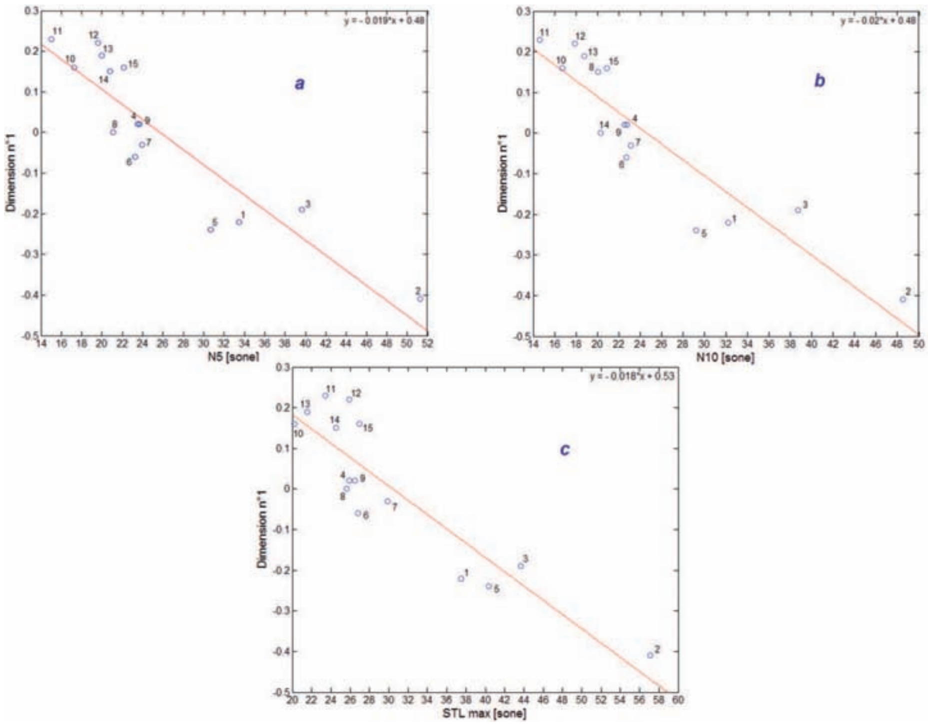


Figure 8.2: Vibroacoustics experiment on *acceleration*: Linear regression between dimension $n°1$ and N5 (a), N10 (b) and STLmax (c). Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

(a), N10 (b) and STLmax (c).

As the first dimension is explained by the unsteady loudness, we decided to enter the r.m.s. and maximum vibrations of seat and of steering wheel s_x, s_y, s_z and sw_x, sw_y, sw_z into the model. Here too, the *Backward* SPSS model is used. Most of the vibration directions play a key role to approximate the second dimension of the *acceleration* vibroacoustic space. Indeed, we obtain a correlation coefficient of 0.65 with the maximum vibrations values. Finally, by doing the same calculation with r.m.s values, the correlation coefficient obtained is 0.6. However, it is difficult to obtain a better correlation coefficient without having to take into account all twelve vibrations values.

Preference study

We use the same procedure as the one explained in Chapter 6 with the *PRESTOOL/Consensus* model. In this paragraph we want to focus on possible differences between preference results of the listening experiment (detailed in Chapter 6) and those of this vibroacoustic experiment. In the same way as for the sound space of *acceleration*, three analyses were undertaken with one, two and three dimensions taking into account one, two and three sub-populations. These different analyses are summarized in Table 8.4. The different analyses give

[2] Root Mean Square.

[3] As already exposed in Chapters 4 and 7, we know the three levels $\overrightarrow{x}$, $\overrightarrow{y}$ and $\overrightarrow{z}$ for seat (s_x,s_y and s_z) and for steering wheel (sw_x, sw_y and sw_z).

Dimension	Error rate [%]	Sub-population (Number of participants)
1	22.7	-
2	22.5	18 and 26
3	22.2	2, 5 and 37

Table 8.4: Error rate and number of participants for each sub-population for the three analyses undertaken with one, two and three dimensions for vibroacoustic *acceleration* experiment.

an error rate of 22.7%, 22.5% and 22.2%, respectively. The analyses with two and three dimensions allow us to have sub-populations of 18 and 26 for the first case and of 2, 5 and 37 for the second one. The preference rankings obtained in the first analysis (with only one dimension) and in the second one (with the group of 26 participants) are really similar. Therefore, we present below the preference rankings with only one dimension. Figure 8.3 presents the results of the listening test (A at top) and the vibroacoustic one (B at bottom).

So, except for some small inversions, notably between $n°1$ and 6, 9 and 4, 11 and 12, the two preference

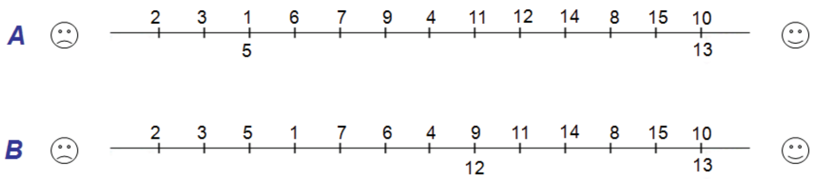


Figure 8.3: Vibroacoustic experiment on *acceleration*: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the listening test A at top (15 stimuli and 38 participants) and the vibroacoustic one B at bottom (15 stimuli and 44 participants). Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

axes of sound and vibroacoustic space for *acceleration* are really similar. As we have seen that the dimension $n°1$ is explained by the unsteady loudness and that this acoustic features is common to both spaces, it is not surprising to find close preference results. The main factor which influences this preference evaluation concerns the sound and not the vibration.

Finally, as for MDS representation and the other preference analyses in Chapter 6, we are interested in results given when we did not take into account the gasoline vehicles $n°13$ and 15. The obtained ranking is exactly the same as seen in Figure 8.4. Moreover, the analysis performed, in order to have two subpopulations give two groups of 8 and 28 participants.

Still, there is no influence of the gasoline cars in the preference ranking. They have been preferred

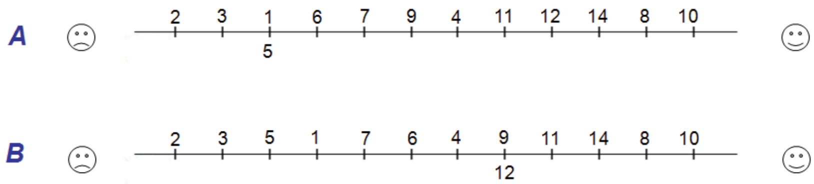


Figure 8.4: Vibroacoustic experiment on *acceleration*: One-dimensional representation of the preferences obtained by the *PRESTOOL/Consensus* analysis for the listening test A at top (13 stimuli and 38 participants) and the vibroacoustic one B at bottom (13 stimuli and 44 participants). Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original) and 14: Renault Grand Scenic.

among other Diesel cars as $n°5$, 10 and 8 for instance, but they do not disrupt the rest of the ranking even by removing them.

This chapter presented results of the multidimensional approach of *acceleration* by comparing acoustic and vibroacoustic perceptual spaces in order to determine the vibrations' influence on the evaluation of Diesel sound (dissimilarity and preference).

Therefore, concerning the *acceleration* case, the dissimilarity experiment has allowed us to obtain a two-dimensional vibroacoustic space with the first dimension well explained by the unsteady loudness N5, N10 and STLmax (with correlation coefficients of -0.91, -0.92 and -0.91, respectively) and the second one, by a linear combination of all seat and steering wheel vibration directions. The first result represents the parameter at order 1 which characterizes the unsteady stimuli. Even if the vibrations' level explain one of the vibroacoustic space's dimension, as for the Dieselness appraisal (Chapter 7), there is no influence of vibrations on the Diesel sound space for *acceleration*.

Conclusion

The work presented in this document deals with the sound perception of Diesel vehicles with a multi-modal and a cross-cultural approach. For several years the interior noise of cars has become an argument put forward by manufacturers and highlighted by the specialized press. It can even have a strong impact on the purchaser's decision and appears almost as one's due for today's user. Indeed, after several fruitful years of sound improvements, especially on sound level reduction, the users' expectations are now different and come even closer to an idea of pleasure. However, the future of the Diesel sound is probably not to copy the gasoline one but to succeed in finding its own personality on which the user can place his imagination and enhance his choice.

Additionally, automotive noise is the result of a superposition of different noise sources: engine, road and air. These sources are transmitted to the driver as noise and vibrations by both airborne and solid pass transfers. Vibrations felt by the Diesel driver are, hence, strongly correlated to the global sensation that he can experience in his car. Therefore, it is difficult to speak of Diesel without tackling vibrations. Besides, I choose a different angle from what is currently treated in scientific community. Instead of studying vibrations' impact on comfort, I focus on vibrations' impact on Dieselness and hedonic judgments in this work. More precisely, the experiments have allowed the participants to assess seat and of steering wheel vibrations.

Finally, the Diesel characteristic has been studied through a cross-cultural work between France and Germany. Working with Oldenburg University has allowed me to reproduce some experiments in both countries in the same conditions in order to focus on the two biggest European Diesel markets.

In order to reach the work's issue, four steps have been presented in four chapters by answering the following questions:

1. When can we recognize Diesel character? (Chapter 5)
2. Which sound space is common for typical driving situations of Diesel? (Chapter 6)
3. What is the influence of vibrations on Dieselness perception? (Chapter 7)
4. What is the influence of vibrations on Dieselness sound space? (Chapter 8)

As precised before, the Diesel vehicle appears as a daily-life sound source that each person may qualify according to his own sensitivity and by his own definition. Therefore, to succeed in describing this particular Diesel sound, it must, above all, know *what* best represents Diesel noise by focusing on *when* people recognize Diesel features (Chapter 5). During a listening experiment, twelve driving situations (*hot idle*, *50-kph*, *70-kph*, *90-kph*, *110-kph* and *130-kph* for the steady ones and *start up the motor*, *stop the motor*, *traffic light start*, *acceleration*, *deceleration* and *traffic jam* for the unsteady ones) of three Diesel cars (a 3-cylinder, a 4-cylinder and a 6-cylinder ones) were realized to identify which driving situation(s) allow a person to realize that a Diesel vehicle is being driven. This sound corpus is representative of the European Diesel market.

The results show that by taking into account all twelve driving situations, *hot idle* best represents Diesel character with assessment close to 90% of Dieselness. Indeed, unquestionably, *hot idle* is approved by a large majority of French and German participants. The other steady situations are only judged weakly as Diesel. Regarding unsteady ones, *acceleration* appears to be the first characteristic driving situation of Dieselness with an assessment of 75%. Therefore, those two situations are the most representative of Diesel feature for both French and German participants. The only difference between both countries lies in the fact that Germans still assess all situations as being more Diesel than the French. However, this difference is not significant. Moreover, for these two driving situations, differences between under-study vehicles are observed for Dieselness appraisal as highlighted by the statistical analysis.

Moreover, both situations are of interest for the scientific community. Indeed, *hot idle* is a condition of use largely studied by the scientific community and automotive industries especially regarding comfort aspects. On the other hand, *acceleration* is a more complex, time-varying situation on which research studies are beginning to show strong expectations, notably regarding non-stationnary loudness. So, this work will contribute to the knowledge of these situations concerning the Dieselness and hedonic issues.

Finally, another interesting result concerns the vehicles' "hierarchy". Indeed, by looking at situation by situation like *hot idle* or *90-kph*, the 6-cylinder car is judged more Diesel than the 3- and the 4-cylinder car. Even if this experiment was realized with three particular vehicles and that it is certainly difficult to generalize these results for all cars of lower, middle and upper classes, this result challenges the *a priori* of automotive experts about the fact that the 3-cylinder car is more Diesel than the 6-cylinder car. For naïve people, it seems not to be having big differences between this two kinds of vehicles. For this reason and for the European antipollution regulations, the downsizing seems to be a good technology on which to work.

Last but not least, this first experiment allows us to assess a methodology with an intermediate recognition phase. Indeed, before evaluating the Diesel character, participants have to recognize the different driving situations presented by choosing a road sign corresponding to the situation that they have just heard. It allows us to ensure the correct interpretation and recognition of steady and unsteady driving situations. The results show that people succeed in discriminating steady from unsteady driving situations. However, it seems more difficult to distinguish speed of stabilized situations. The same difficulty can be observed for unsteady situations such as *acceleration* and *traffic light start*. We have explained these low percentages for correct answers by the stimuli themselves which appear very similar to two distinct road signs. Recognition of situations like *start up the motor* and *stop the motor* seem more obvious. However, let's precise here that this identification phase was uncorrelated to the Dieselness evaluation. It would be interesting to perform this test by asking participants to choose a road sign and assess Dieselness only once for each presented stimulus. Indeed, this could provide more information on their frame of reference and evaluation's strategy of Dieselness.

After having found two driving situations which best represent Dieselness, we have pursued with the study of the respective sound spaces of *hot idle* and *acceleration* in order to explain their perceptual dimensions and of preference. Indeed, this second step consists in focusing on those elementary driving situations in order to describe their particularities which make the Diesel identity. To succeed in this quest, the representation of its particular sound through a multidimensional approach is chosen. Indeed, it seems important to determine the sound dimensions which are relevant from a perceptual point of view (close to the *timbre* notion). Each of the two driving situations is treated separately.

Concerning the *hot idle* case, the dissimilarity experiment has allowed to obtain a two-dimensional perceptual sound space with a first dimension explained by the engine revolution speed [RPM], *i.e.* the pitch, with a correlation coefficient of 0.70 or even, with a better correlation coefficient of 0.81, the modulation frequency calculated on the octave 1000. The second dimension appears as being difficultly explained by only one descriptor. With the *Backward* model of SPSS software, the results showed that this dimension is approximated with a linear combination of modulation frequency and specific emergence. The first dimension confirms the different studies performed on Diesel sound of *hot idle* notably on comfort.

Moreover, as we have expected, there is a strong correlation between this modulation and the preference. The more modulation that is present, the lower the participant's preference. In addition, the preference rating confirms the three groups of vehicles with these from Lower classification (represented by the 3-cylinder cars), these from the Middle one (represented by the 4-cylinder cars) and these from the Upper ones (represented by the 6-cylinder cars) and to the gasoline vehicles. Finally, the modulation feature is characteristic of 3-cylinder cars therefore this type of vehicle suffers from its engine geometry which creates an irregular sound.

Concerning the *acceleration* case, the multidimensional scaling results give a two-dimensional perceptual sound space. These dimensions are respectively explained or approximated (i) by the unsteady loudness (either N5, N10 or STLmax) with correlation coefficient of -0.93, -0.93 and -0.91, respectively, and by (ii) a linear combination of averaged envelop and length before the change of the gear with a correlation coefficient of only 0.44. Here too, the dimension explained by the non-stationary loudness was predictable since no equalization of loudness was done. Therefore, this parameter appears at order 1 and better characterizes the unsteady stimuli than the various experiments treated in the scientific literature.

Finally, as we have expected, the preference is explained by the different descriptors of loudness. The greater the sound level, the less the participant appreciates the vehicle. This result confirms the great influence of this parameter during the sound experiments already revealed in scientific literature. However, this unsteady descriptor is one of the main topics of research in Psychoacoustics.

Moreover, this multidimensional scaling allows us to investigate two other factors: the subwoofer's influence on automotive context and the gasoline vehicles' impact among various Diesel cars. First, by presenting a vehicle with and without its very low frequencies (<70Hz), we could notice that this vehicle is still evaluated in the same manner (with and without low frequencies). Therefore, this result allows to conclude that there is no influence of subwoofer on dissimilarity and preference experiments in laboratory context. Secondly, the gasoline car's impact is qualified. Results show that gasoline cars are not perceived really different from Diesel ones in the *hot idle* case. Indeed, with and without gasoline cars in the perceptual sound space, the repartition of the different vehicles is homogeneous enough. However, this conclusion is less true for the *acceleration* case. They are perceived different from Diesel ones along the second dimension, characterized by the combination of averaged envelop and length before the change of the gear. So, this difference has its origin in those parameters. It would be interesting to pursue this direction of work by introducing more gasoline cars in order to homogenize the number of Diesel and gasoline cars. To conclude on this point, let's precise that these gasoline vehicles match the Diesel ones. The only difference between these vehicles was the engine.

After having found two driving situations which best represent Dieselness, we were interested in the vibrations' influence on this Dieselness appraisal. Are *hot idle* and *acceleration* still the best representatives of Diesel character? The case of seat and steering wheel vibrations, which are described as the main vibrations contributors in the literature, was investigated. By asking people to rate Dieselness among a stimuli corpus made up of both sound and vibroacoustic stimuli, we allowed the study of the vibrations' influence. For more convenience, six driving situations of the same three Diesel cars from before have been evaluated through a perceptual vibroacoustic experiment. Results show similar tendencies for French and German people. First of all, vibrations lead to slightly higher evaluations. However, statistical analysis highlights its influence on Dieselness evaluation but shows only a weak impact on it. In addition, vibrations' effect depends on different parameters: kind of Diesel cars (3-, 4- or 6-cylinder car) and driving situation. Indeed, the vibration effect is more important for the 4-cylinder car and the 6-cylinder car than for the 3-cylinder vehicle.

Despite some differences, the French and Germans totally agree with the fact that *hot idle* is the most Diesel-like driving situation, whatever the modality and whatever the vehicle. But all results must be taken with caution because we refer to only one 3-cylinder, one 4-cylinder and one 6-cylinder car. Finally, the main conlusion is that the Dieselness evaluation was made on the first order with one sound component.

Finally, after having obtained the respective sound space of *hot idle* and *acceleration* with parameters which explain the perceptual dimensions and the preference evaluation, we have pursued with the same multidimensional scaling approach by introducing vibrations. Indeed, in the same way as the Dieselness question, we want to know if seat and steering wheel vibrations have some influence on perceptual sound space and on preference appraisals. For different reasons exposed in Chapter 8, we have treated only the *acceleration* that we have been able to compare with perceptual sound space results of *acceleration*. Indeed, the dissimilarity experiment has allowed me to obtain a two-dimensional vibroacoustic space with the first dimension well explained by the unsteady loudness with comparable correlation coefficients for N5, N10 and STLmax. Therefore, it still appears as the parameter at order 1 which characterizes the unsteady stimuli. On the other hand, the second dimension is approximated (with a correlation coefficient of 0.6) by a linear combination of vibrations. In addition, this is especially the $\overrightarrow{x}$ direction of the steering wheel which is the most contributor to distinguish the vehicle along the dimension $n°2$.

Last but not least, the comparison between the perceptual sound space and the perceptual vibroacoustic one does not show real differences except for two particular stimuli. So, as for Dieselness appraisal, there is no noticeable influence of vibrations on the Diesel sound space in the case of *acceleration*.

Here too, we have focused on the subwoofer and the gasoline cars' influence on the perceptual multidimensional space. In the same way as for the acoustic space, the vibroacoustic one does not show an influence of subwoofer on dissimilarity and preference experiments in a laboratory context. In addition, the gasoline cars are perceived different from Diesel ones along the second dimension and is characterized by the combination of different directions of vibrations. In the same way as for acoustic space, it would be interesting to pursue this direction of work by introducing more gasoline cars.

To conclude, the main contributions of this thesis work and the perspectives of work are:

- use almost one methodology per experiment with some accomodations,
- define driving situations representative of daily-life use of a car by the European customers,
- identify two driving situations representative of Diesel character: *hot idle* and *acceleration*,
- show the small difference, for naïve people, between a 3-cylinder and a 6-cylinder car,
- prove the weak influence of seat and steering wheel vibrations about the Dieselness evaluation,
- indicate the weak influence of seat and steering wheel vibrations on multidimensional space and of preference ratings;

These different contributions allow to know which it would be interesting to do in order to pursue in this way. Let's focus on some interesting points to highlight. The main perspectives are:

- focus on acoustic modality during Diesel study without taking into account seat and steering wheel vibrations. Indeed, this main conclusion will allow to simplify experiment's protocols and setups without a test bench. Thanks to it, this result reinforces the interest of sound design as tool to improve the Diesel identity;
- wonder if it is still judicious to work on active control to design vibrations which do not contribute to Diesel features. However, it is still an open question concerning the comfort;
- study a wider sound corpus by introducing more gasoline vehicles. As we have seen before, we should obtain in the same way an homogeneous multidimension space since gasoline cars seemed to be not so different from the Diesel ones;
- use more various Diesel vehicles by taking into account the different sounds between German, Italian and French cars. In addition, the future generalization of the downsizing of engines and electric cars will contribute to a new sound environment, unheard-of and with no investigation;
- use the verbalizations of the participants in order to better explain the dimensions of the multidimensional spaces;

- have another approach with *in-situ* experiments in genuine vehicles to confirm laboratory results for *acceleration*. Indeed, *hot idle* case might become irrelevant in the future with the spread of stop & start systems;
- perform the without limiting himself to Diesel drivers and recruit gasoline drivers to take into account a possible difference in driving and sound habits;
- carry out a cross-cultural study with people from Asia or America to confirm (i) differences between gasoline and Diesel markets and (ii) more important cultural differences.

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Appendix A

QUESTIONNAIRE SUJET n° ___

1- Sexe : ☐ Homme ☐ Femme

2- Quel est votre âge ?

3- Depuis combien d'années avez-vous le permis de conduire ?

4- Vous conduisez ?
- ☐ très peu (moins d'une fois par mois)
- ☐ occasionnellement (au moins une fois par mois)
- ☐ régulièrement (au moins une fois par semaine)
- ☐ tous les jours

5- Parmi les 3 affirmations suivantes, laquelle vous correspond le plus ?
- ☐ conduire est souvent un plaisir
- ☐ conduire est un plaisir de temps en temps, dans certaines circonstances

Précisez dans quelles circonstances :

- ☐ conduire n'est jamais un plaisir

6- Pouvez-vous estimer votre kilométrage par an :

7- Quels sont la marque et le modèle de votre véhicule ?

8- De quelle année date votre véhicule (date de la première immatriculation de votre véhicule) ?

9- Le moteur de votre véhicule est-il ?
- ☐ essence
- ☐ diesel
- ☐ hybride
- ☐ ne sait pas : *Quel est le carburant que vous mettez dans votre réservoir ?*

10- Avez-vous toujours eu ce type de motorisation ?
□ OUI □ NON

*Pourquoi ce **choix** de motorisation :*

*Pourquoi ce **changement** de motorisation :*

11- Lorsque vous entrez dans votre véhicule, mettez-vous en marche la radio / le lecteur CD ?
□ jamais □ rarement □ souvent □ automatiquement

12- Qu'écoutez-vous le plus (lorsque vous mettez en marche votre radio / lecteur CD) ?
□ radios plutôt informatives / sportives (beaucoup plus de parole que de musique)
□ radios plutôt musicales ou CD (beaucoup plus de musique que de parole)

SONORITE INTERIEURE : le bruit à l'intérieur du véhicule

13- Quelle importance donnez-vous à la sonorité à l'intérieur d'un véhicule ?
□ pas important □ peu important □ important □ très important

14- Est-ce que la sonorité à l'intérieur de votre véhicule vous plaît ?
□ OUI □ NON

Décrivez ce qui vous plaît :

Décrivez ce qui vous déplaît :

15- Comment décririez-vous le son intérieur idéal ?

SONORITE EXTERIEURE : le bruit à l'extérieur du véhicule

16- Quelle importance donnez-vous à la sonorité à l'extérieur d'un véhicule ?
□ pas important □ peu important □ important □ très important

17- Avez-vous une idée précise de la sonorité à l'extérieur de votre véhicule ?
□ OUI □ NON

18- Est-ce que la sonorité à l'extérieur de votre véhicule vous plaît ?
□ OUI □ NON

Décrivez ce qui vous plaît :

Décrivez ce qui vous déplaît :

19- Comment décririez-vous le son extérieur idéal ?

Remarques, suggestions :

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Appendix B

MISE EN SITUATION

Bonjour,

Imaginez-vous au volant d'un véhicule en accélération, nous vous demandons de juger « **l'ambiance sonore** » **intérieure** de ce véhicule. Installez vous bien au fond du siège comme si vous conduisiez.

Ce test se compose d'une partie. Il vous est demandé d'écouter les 8 sons et de regrouper ces sons dans des catégories que vous allez créer sur le principe du « qui se ressemble s'assemble ».

Déroulement

- Vous pouvez écouter autant de fois que vous voulez et dans n'importe quel ordre chacun des sons numérotés en cliquant dessus.
- Regroupez les sons dans des catégories : pour cela, vous pouvez vous aider des petits dés numérotés pour créer vos catégories sur la tablette face à vous puis écrire les catégories créées en reportant les numéros des sons sur votre feuille.
- Essayez de créer plus de deux catégories.
- Essayez aussi de ne pas avoir de catégories avec un seul son.
- Après avoir fait vos catégories, décrivez-les par un mot, par une phrase… Expliquez ce qui a fait que vous avez réuni certains sons dans la catégorie A, d'autres dans la catégorie B, etc...
- **Contacter l'hôtesse** une fois l'ensemble des sons traités ou en cas de problème.

! Il n'y a pas de mauvaises réponses.

N'hésitez pas à faire une **petite pause** à la moitié du test si vous le souhaitez : vous pouvez sortir de la salle, aller prendre l'air dehors, l'hôtesse vous accompagnera.

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Appendix C

Cars manufacturer	Vehicle model	Engine	Cylinders' geometry	Powerful	Gearbox	Car Classification
Hyundai	Getz	Diesel	L3	82	5-speed manual	Lower
Hyundai	I10	Diesel	L3	75	5-speed manual	Lower
Kia	Picanto	Diesel	L3	75	5-speed manual	Lower
Chevrolet	Matiz	Gasoline	L3	51	5-speed manual	Lower
Mitsubishi	I	Gasoline	L3	64	4-speed automatic	Lower
Toyota	Aygo	Gasoline	L3	68	5-speed manual	Lower
Citroën	C1	Diesel	L4	54	5-speed manual	Lower
Citroën	C4	Diesel	L4	110	6-speed automatic	Middle
Citroën	C5	Diesel	L4	110	5-speed manual	Middle
Citroën	C-Crosser	Diesel	L4	156	6-speed manual	Middle
Fiat	500	Diesel	L4	75	5-speed manual	Lower
Ford	Fiesta	Diesel	L4	68	5-speed manual	Lower
Kia	Rio	Diesel	L4	110	5-speed manual	Lower
Nissan	Micra	Diesel	L4	82	5-speed manual	Lower
Nissan	Note	Diesel	L4	86	5-speed manual	Lower
Opel	Corsa	Diesel	L4	90	6-speed manual	Lower
Peugeot	207	Diesel	L4	110	5-speed manual	Lower
Peugeot	308	Diesel	L4	110	6-speed manual	Middle
Peugeot	407 SW	Diesel	L4	170	6-speed manual	Middle
Renault	Clio	Diesel	L4	105	6-speed manual	Middle
Renault	Espace	Diesel	L4	175	6-speed manual	Upper
Renault	Laguna	Diesel	L4	150	6-speed automatic	Middle
Renault	Modus	Diesel	L4	85	5-speed manual	Lower
Renault	Grand Scenic	Diesel	L4	130	6-speed manual	Middle
Renault	Twingo 2	Diesel	L4	65	5-speed manual	Lower
Renault	Velsatis	Diesel	L4	150	6-speed manual	Upper
Renault	Velsatis	Diesel	L4	175	6-speed manual	Upper
Subaru	Legacy	Diesel	L4	150	5-speed manual	Upper
Toyota	Corolla	Diesel	L4	90	5-speed manual	Middle

Cars manufacturer	Vehicle model	Engine	Cylinders' geometry	Powerful	Gearbox	Car Classification
Citroën	C2	Gasoline	L4	110	5-speed automatic	Lower
Citroën	C3	Gasoline	L4	75	5-speed manual	Lower
Peugeot	207 CC	Gasoline	L4	150	5-speed manual	Lower
Peugeot	307 CC	Gasoline	L4	136	6-speed manual	Middle
Toyota	Yaris	Gasoline	L4	87	4-speed automatic	Lower
VW	Golf	Gasoline	L4	170	6-speed manual	Middle
Volvo	XC90	Diesel	L5	180	6-speed manual	Upper
BMW	530D	Diesel	L6	218	6-speed automatic	Upper
Mercedes	320	Diesel	L6	224	7-speed automatic	Upper
Audi	A4	Diesel	V6	190	8-speed automatic	Middle
Citroën	C6	Diesel	V6	208	6-speed automatic	Upper
Hyundai	Veracruz	Diesel	V6	240	6-speed automatic	Upper
Peugeot	407 Coupé	Diesel	V6	204	6-speed automatic	Middle
Lexus	ES330	Gasoline	V6	228	6-speed automatic	Upper
Lexus	RX300	Gasoline	V6	220	6-speed automatic	Upper
Nissan	Infinity	Gasoline	V6	280	5-speed automatic	Upper
Honda	Accord	Hybrid	V6	255	5-speed automatic	Middle
Lexus	RX400	Hybrid	V6	214	6-speed automatic	Upper

Appendix D

Consigne du Test d'écoute

But de l'expérience :

Le but de cette expérience est d'identifier la ou les situation(s) de conduite les plus représentatives de la sonorité d'un moteur Diesel.

Mise en situation :

Imaginez-vous au volant d'une voiture. Les évènements sonores représentent des sons que vous pouvez entendre lorsque vous êtes au volant d'une voiture. Ils correspondent à des situations de conduite typiques que vous pouvez rencontrer en ville et en dehors des villes.

Déroulement de l'expérience :

Vous allez écouter deux séquences sonores. Chacune est composée de plusieurs évènements sonores séparés par des micro-coupures d'une seconde. Une séquence sonore dure un peu plus de 5 minutes au total.

Les évènements sonores (qui constituent une séquence) sont issus d'enregistrements d'un véhicule Diesel.

Dans l'expérience, vous aurez à évaluer deux séquences sonores (c'est-à-dire deux véhicules Diesel différents).

Pour chacune de ces deux séquences, vous aurez à effectuer les 3 étapes suivantes :

Etape 1 :
Votre tâche consiste seulement à écouter la séquence sonore dans son ensemble.

Etape 2 :
Vous allez maintenant réécouter successivement les 16 évènements sonores de l'Etape 1. Par ailleurs, vous disposez d'un ensemble de panneaux de signalisation routière. Il vous est demandé de choisir le panneau signalétique qui correspond le plus à la situation de conduite que vous venez d'entendre. Il vous sera possible (si vous le souhaitez) d'écouter plusieurs fois le même son, avant de choisir le panneau signalétique correspondant.

Etape 3 :
Vous allez maintenant écouter successivement ces mêmes évènements sonores. Pour chacun de ces évènements sonores, il vous est demandé de donner un jugement comme réponse à la question suivante :

Dans quelle mesure cet évènement sonore correspond-t-il à une situation de conduite représentative de la sonorité d'un moteur Diesel ? Autrement dit, dans quelle mesure évoque-t-il une sonorité de Diesel ? Dans quelle mesure cet évènement permet-il de vous rendre compte que vous êtes au volant d'un Diesel ?

Donnez votre jugement sur une échelle entre 0 et 10 avec :

* 0 qui indique que vous trouvez que l'évènement sonore n'évoque pas du tout une sonorité de moteur Diesel,
* 10 qui indique que vous trouvez que l'évènement sonore évoque parfaitement une sonorité de moteur Diesel.

Remarque : Nous vous demandons de porter votre attention exclusivement sur la sonorité Diesel des évènements sonores et non pas sur des aspects de préférence ou sur l'intensité des évènements sonores.

L'évaluation de la première séquence sonore est terminée.
Si vous le désirez, vous pouvez prendre une pause de quelques minutes avant de passer à l'évaluation de la deuxième séquence sonore pour laquelle vous réitérerez les mêmes étapes.

Remarque : **A la fin de cette expérience, nous pourrons échanger quelques minutes sur vos impressions concernant le test (facilité/difficulté du test,...).**

MERCI DE VOTRE PARTICIPATION !!!

Versuchsanleitung

Ziel des Experimentes :

Das Ziel dieses Experimentes ist es, herauszufinden, in welcher/n Fahrsituation/en der Klang eines Dieselmotors besonders auffällt.

Versetzen Sie sich in folgende Situation :

Stellen Sie sich vor, dass Sie am Steuer eines Autos sitzen. Die dargebotenen Geräusche sind typische Geräusche am Steuer eines Wagens. Sie entsprechen Geräuschen typischer Fahrsituationen, die in Ortschaften oder außerhalb von Ortschaften vorkommen.

Ablauf des Experimentes :

Sie werden zwei Serien von Fahrgeräuschen hören. Jede ist aus mehreren Fahrgeräuschabschnitten zusammengestellt, die jeweils durch kurze, eine Sekunde lange Pausen voneinander getrennt sind. Eine Fahrgeräuschserie dauert insgesamt etwas mehr als 5 Minuten.

Die Fahrgeräuschabschnitte, die zusammen eine Fahrgeräuschserie bilden, stammen aus Aufnahmen in einem Dieselfahrzeug.

Während des Experimentes sollen Sie zwei Fahrgeräuschserien bewerten und damit zwei unterschiedliche Dieselfahrzeuge.

Für jede der beiden Fahrgeräuschserien werden 3 Versuchsabschnitte durchlaufen :

1. Versuchsabschnitt :
Ihre Aufgabe besteht lediglich darin, sich die gesamte Fahrgeräuschserie einmal anzuhören.

2. Versuchsabschnitt :
Sie werden die 16 Geräuschabschnitte der Fahrgeräuschserie des 1. Versuchsabschnittes noch einmal einzeln hören. Ihnen stehen gleichzeitig eine Auswahl von Verkehrszeichen zur Verfügung. Bitte wählen Sie das Verkehrszeichen aus, das der Fahrsituation, die Sie gerade hören, am besten entspricht. Wenn Sie möchten, können Sie sich den jeweiligen Geräuschabschnitt mehrere Male anhören, bevor Sie das entsprechende Verkehrszeichen wählen.

3. Versuchsabschnitt :
Sie werden jetzt diese Geräuschabschnitte wieder nacheinander einzeln hören. Beantworten Sie bitte für jeden Geräuschabschnitt folgende Frage:

"In welchem Maße entspricht dieser Geräuschabschnitt einer Fahrsituation, bei der der typische Klang eines Dieselfahrzeugs zu hören ist? Oder anders gefragt: In welchem Maße klingt es wie ein Diesel? In welchem Maße gibt Ihnen dieser Geräuschabschnitt das Gefühl, dass Sie am Steuer eines Dieselfahrzeugs sitzen?"

Geben Sie Ihr Urteil auf einer Skala von 0-10 ab, wobei:
* 0 bedeutet: Sie finden, dass sich dieser Geräuschabschnitt überhaupt nicht wie ein Dieselgeräusch anhört,
* 10 bedeutet: Sie finden, dass dieser Geräuschabschnitt genau wie ein Dieselgeräusch klingt.

Bemerkung : Bitte richten Sie Ihre Aufmerksamkeit ausschließlich auf den Dieselklang der Geräuschabschnitte und nicht darauf, ob Sie ihn mehr oder weniger mögen, oder ob er lauter oder leiser ist.

Die Beurteilung der ersten Fahrgeräuschserie ist jetzt beendet.
Wenn Sie möchten, können Sie ein paar Minuten pausieren, bevor Sie zur Beurteilung der zweiten Fahrgeräuschserie mit den drei Versuchsabschnitten wie bei der ersten Fahrgeräuschserie übergehen.

Bemerkung : **Am Ende dieses Experimentes können wir uns einige Minuten über Ihre Eindrücke zum Versuch (Einfachheit, Schwierigkeit des Tests ...) austauschen.**

HERZLICHEN DANK FÜR IHRE TEILNAHME !!!

Appendix E

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.036	0.036	0.216	0.6548	0.20
P	8	1.328	0.166			7.33
V	1	0.118	0.118	1.990	0.1960	0.65
V x C	1	0.041	0.041	0.695	0.4286	0.23
V x P	8	0.476	0.059			2.63
S	11	7.548	0.686	12.506	0.001	41.65
S x C	11	0.580	0.053	0.961	0.4878	3.20
S x P	88	4.829	0.055			26.65
V x S	11	0.622	0.057	2.310	0.0154	3.43

Table 8.6: ANOVA table for combination 3/4 with C: Combinations' order, P: French participants, V: vehicle (with 3 or 4 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.146	0.146	0.466	0.5140	0.85
P	8	2.497	0.312			14.50
V	1	0.157	0.157	2.607	0.1451	0.91
V x C	1	$3.50*10^{-4}$	$3.50*10^{-4}$	0.006	0.9410	0.00
V x P	8	0.480	0.060			2.79
S	11	5.176	0.471	10.507	0.0001	30.05
S x C	11	0.794	0.072	1.612	0.1092	4.61
S x P	88	3.941	0.045			22.88
V x S	11	1.296	0.118	5.141	0.0001	7.52

Table 8.7: ANOVA table for combination 4/6 with C: Combinations' order, P: French participants, V: vehicle (with 4 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.016	0.016	0.307	0.5945	0.08
P	8	0.408	0.051			2.17
V	1	0.092	0.092	2.920	0.1258	0.49
V x C	1	0.002	0.002	0.048	0.8328	0.01
V x P	8	0.252	0.032			1.34
S	11	10.482	0.953	16.788	0.001	55.82
S x C	11	0.094	0.009	0.151	0.9993	0.50
S x P	88	4.995	0.057			21.27
V x S	11	0.578	0.053	2.879	0.0028	3.08

Table 8.8: ANOVA table for combination 3/6 with C: Combinations' order, P: French participants, V: vehicle (with 3 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Appendix F

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.040	0.040	0.390	0.5495	0.18
P	8	0.810	0.101			3.67
V	1	0.034	0.034	0.928	0.3635	0.15
V x C	1	0.046	0.046	1.251	0.2959	0.21
V x P	8	0.294	0.037			1.33
S	11	14.336	1.303	42.393	0.0001	64.91
S x C	11	0.247	0.022	0.730	0.7066	1.12
S x P	88	2.705	0.031			12.25
V x S	11	1.294	0.118	5.029	0.0001	5.86

Table 8.9: ANOVA table for combination 3/4 with C: Combinations' order, P: German participants, V: vehicle (with 3 or 4 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.180	0.180	2.042	0.1909	0.82
P	8	0.707	0.088			3.22
V	1	0.114	0.114	6.362	0.0357	0.52
V x C	1	0.031	0.031	1.739	0.2237	0.14
V x P	8	0.144	0.018			0.66
S	11	14.120	1.284	45.298	0.0001	64.32
S x C	11	0.314	0.029	1.009	0.4454	1.43
S x P	88	2.494	0.028			11.36
V x S	11	2.254	0.205	12.661	0.0001	10.27

Table 8.10: ANOVA table for combination 4/6 with C: Combinations' order, P: German participants, V: vehicle (with 4 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.004	0.004	0.026	0.8748	0.02
P	8	1.259	0.157			5.95
V	1	0.376	0.376	5.305	0.0502	1.78
V x C	1	0.021	0.021	0.290	0.6051	0.10
V x P	8	0.567	0.071			2.68
S	11	12.450	1.132	26.227	0.0001	58.88
S x C	11	0.359	0.033	0.757	0.6812	1.70
S x P	88	3.797	0.043			17.96
V x S	11	0.807	0.073	3.115	0.0014	3.82

Table 8.11: ANOVA table for combination 3/6 with C: Combinations' order, P: German participants, V: vehicle (with 3 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Appendix G

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.075	0.075	0.598	0.4498	0.19
P	1	0.002	0.002	0.013	0.9121	0.00
V	1	0.140	0.140	2.773	0.1142	0.35
V x C	1	$6.021*10^{-5}$	$6.021*10^{-5}$	0.001	0.9728	0.00
V x P	1	0.013	0.013	0.252	0.6220	0.03
S	11	21.081	1.916	45.728	0.0001	52.43
S x C	11	0.523	0.048	1.135	0.3360	1.30
S x P	11	0.802	0.073	1.741	0.0675	1.99
V x S	11	1.786	0.162	6.854	0.0001	4.44

Table 8.12: ANOVA table for combination 3/4 with C: Combinations' order, P: French and German participants, V: vehicle (with 3 or 4 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.001	0.001	0.005	0.9473	0.00
P	1	0.181	0.181	0.870	0.3640	0.46
V	1	0.269	0.269	7.115	0.0162	0.68
V x C	1	0.013	0.013	0.330	0.5730	0.03
V x P	1	0.002	0.002	0.044	0.8371	0.00
S	11	17.544	1.595	41.384	0.0001	44.56
S x C	11	0.336	0.031	0.793	0.6473	0.85
S x P	11	1.752	0.159	4.132	0.0001	4.45
V x S	11	3.328	0.303	14.009	0.0001	8.46

Table 8.13: ANOVA table for combination 4/6 with C: Combinations' order, P: French and German participants, V: vehicle (with 4 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
C	1	0.018	0.018	0.183	0.6738	0.04
P	1	1.083	1.083	11.034	0.0040	2.60
V	1	0.420	0.420	8.660	0.0091	1.00
V x C	1	0.017	0.017	0.342	0.5666	0.04
V x P	1	0.048	0.048	0.990	0.3338	0.12
S	11	22.303	2.028	41.744	0.0001	53.45
S x C	11	0.163	0.015	0.305	0.9842	0.39
S x P	11	0.628	0.057	1.176	0.3061	1.50
V x S	11	1.237	0.112	5.490	0.0001	2.96

Table 8.14: ANOVA table for combination 3/6 with C: Combinations' order, P: French and German participants, V: vehicle (with 3 or 6 cylinders), S: driving situation, SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Appendix H

<u>Consigne du test perceptif</u>

Jugements de dissemblance
et de préférence sur des paires de sons

<u>But de l'expérience :</u>

Cette expérience consiste à <u>évaluer la dissemblance</u> entre des paires de sons et à faire un <u>jugement de préférence</u> sur ces paires de sons.

<u>Mise en situation :</u>

Imaginez-vous au volant d'une voiture. Installez-vous bien au fond du siège comme si vous conduisiez.

<u>Procédure à suivre pour réaliser un jugement de dissemblance et de préférence :</u>

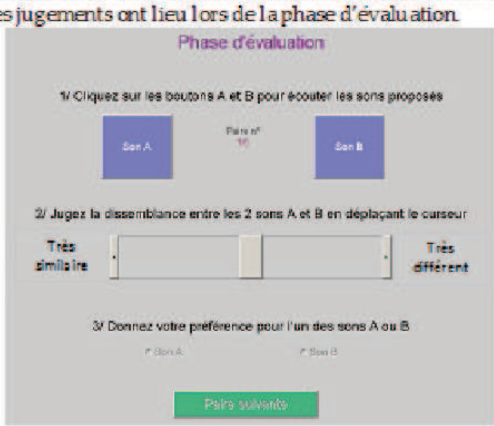
- Ecoutez attentivement les sons «son A» et «son B» ;
- Vous devez <u>en premier</u>, juger la dissemblance (ou la similarité) entre ces deux sons ;
- Le jugement se fait en déplaçant un curseur entre le pôle «Très similaire» et le pôle «Très différent». Plus vous jugez que la différence entre les deux sons est grande, plus vous devez placer le curseur près du pôle «Très différent» ;
- Vous pouvez réécouter la paire de sons «son A» et «son B» autant de fois que vous le souhaitez. Quand vous êtes satisfait de votre jugement de dissemblance, vous pouvez <u>ensuite</u> passer au jugement de préférence ;
- Choisissez le son que vous préférez en cliquant sur «son A» ou «son B». Quand vous êtes satisfait de votre jugement de préférence, cliquez sur «Paire suivante».

Déroulement global de l'expérience :

Dans un premier temps, une phase d'écoute vous est proposée. Vous allez écouter tous les sons de l'expérience. Ceci vous permet de vous faire une idée du panel de sons que

- vous évaluerez après et ainsi, utiliser la totalité de l'échelle proposée pour réaliser les jugements de dissemblance ;

- L'expérience proprement dite, consiste à effectuer 105 jugements de dissemblance et de préférence. Ces jugements ont lieu lors de la phase d'évaluation.



Remarque : Nous vous demandons de porter votre attention exclusivement sur les sons en eux-mêmes et non sur l'intensité de ces sons ou sur des bruits parasites qui pourraient être présents, par exemple.

Contacter l'hôtesse une fois l'expérience terminée ou en cas de problème.

Il n'y a pas de mauvaises réponses, chaque réponse est une bonne réponse.

Remarque : A la fin de l'expérience, nous prendrons quelques minutes ensemble pour parler de vos impressions sur le test.

MERCI DE VOTRE PARTICIPATION !!!

Appendix I

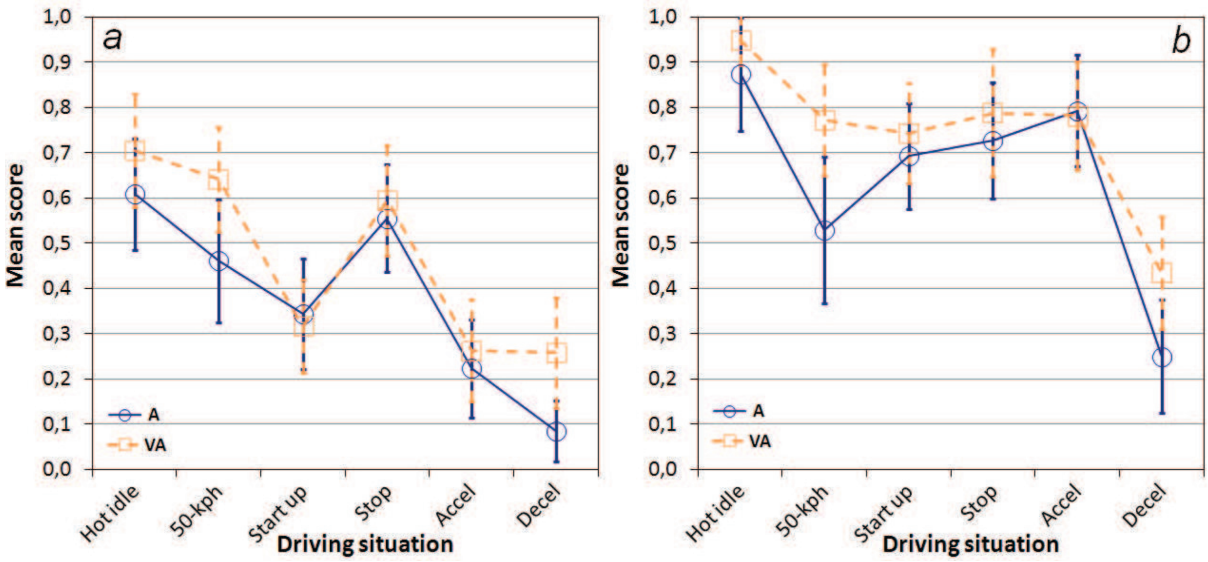


Figure 8.5: Dieselness mean scores and standard deviations obtained for Renault Mégane gasoline (a) and Renault Mégane Diesel (b).

Appendix J

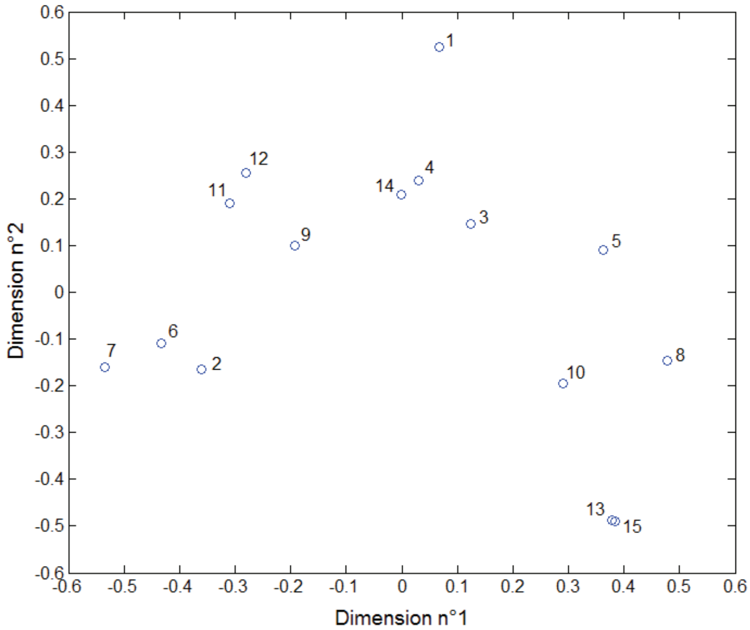


Figure 8.6: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *hot idle* and for the 5 participants of the 1^{st} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

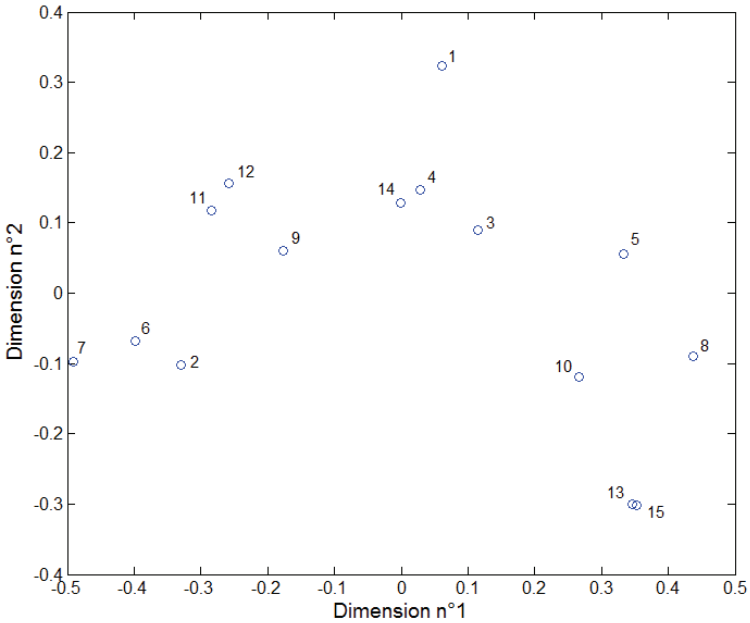


Figure 8.7: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *hot idle* and for the 17 participants of the 2^{nd} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

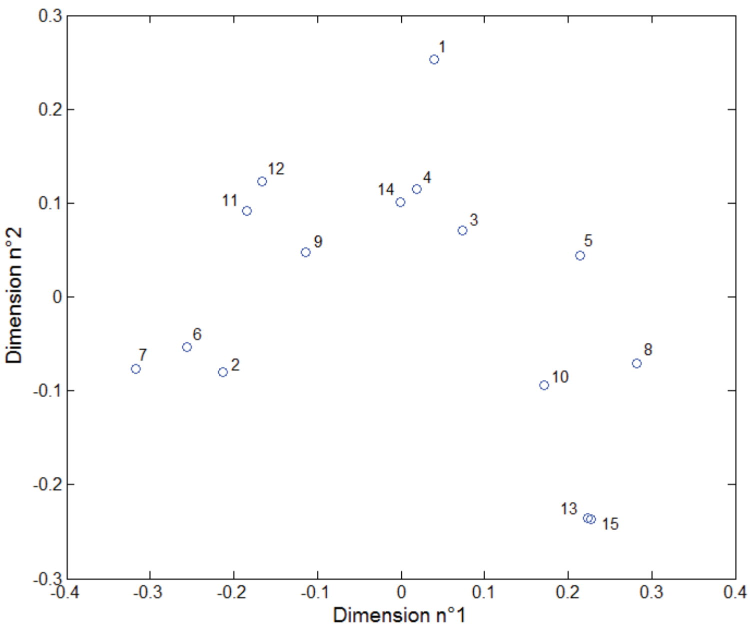


Figure 8.8: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *hot idle* and for the 14 participants of the 3^{rd} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

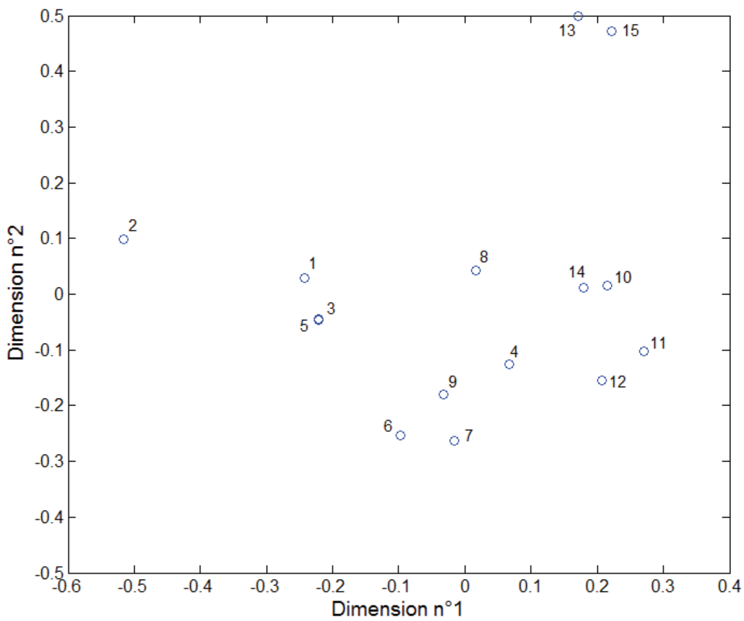


Figure 8.9: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *acceleration* and for all participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

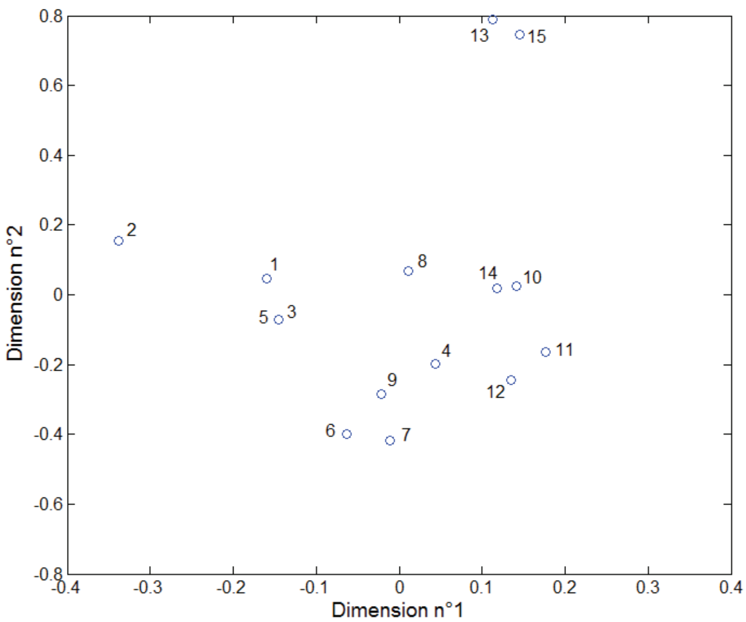


Figure 8.10: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *acceleration* and for 4 participants of the 1^{st} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

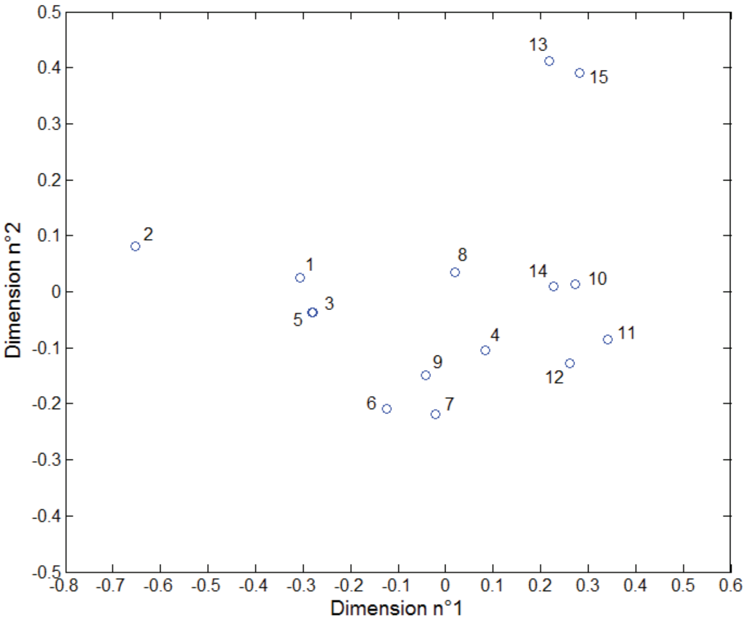


Figure 8.11: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *acceleration* and for 12 participants of the 2^{nd} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

Appendix K

Consigne du test perceptif

But de l'expérience :

Le but de ce test perceptif est d'identifier la ou les situation(s) de conduite les plus caractéristiques de moteurs diesel, en se basant sur le bruit perçu et les vibrations ressenties.

Mise en situation :

Prenez place sur le siège du banc d'essai. Réglez le siège afin d'être confortablement installé (nous vous demandons de ne régler que la distance entre le siège et le volant et de ne pas modifier l'inclinaison du siège). Posez vos mains sur le volant aux deux endroits indiqués par les deux marques de scotch. Enfin, posez vos pieds à plat sur la plateforme.

Imaginez-vous à l'intérieur d'une voiture. Les évènements (sonores et sonores&vibratoires) qui vont vous être présentés au niveau du casque, du volant et du siège, reproduisent des sensations que vous pouvez ressentir lorsque vous êtes à l'intérieur d'une voiture. Ils correspondent à des situations de conduite typiques que vous pouvez rencontrer en ville et en dehors des villes.

Déroulement de l'expérience :

Le test se déroule en deux étapes.

Etape 1 :
Quelques évènements (sonores et sonores&vibratoires) que vous aurez à évaluer dans l'Etape 2, vous sont présentés. Votre tâche, ici, consiste seulement à écouter et ressentir ces différents évènements (sonores et sonores&vibratoires). Cette étape permet de vous faire une idée du panel d'évènements que vous évaluerez après.

Etape 2 :
Les évènements (sonores et sonores&vibratoires) vous sont présentés un à un dans cette étape. Pour chacun de ces évènements, il vous est demandé de donner un jugement comme réponse à la question suivante :
Dans quelle mesure cet évènement correspond-t-il à une situation de conduite représentative d'un moteur diesel ? Autrement dit, dans quelle mesure évoque-t-il le moteur diesel ? Dans quelle mesure cet évènement permet-il de vous rendre compte que vous êtes au volant d'un diesel ?

Donnez votre jugement sur une échelle entre 0 et 10 avec :

* 0 qui indique que vous trouvez que l'évènement n'évoque pas du tout un moteur diesel,
* 10 qui indique que vous trouvez que l'évènement évoque parfaitement un moteur diesel.

Remarque : Nous vous demandons de porter votre attention exclusivement sur les sons et les vibrations des évènements présentés et non pas sur des aspects de préférence ou sur l'intensité des évènements.

Remarque : A la fin du test, nous prendrons quelques minutes ensemble pour connaître vos impressions sur ce test.

MERCI DE VOTRE PARTICIPATION !!!

Versuchsanleitung

Ziel des Experimentes :

Das Ziel dieses Wahrnehmungsexperimentes ist es, aufgrund der wahrgenommenen Geräusche und Vibrationen herauszufinden, welche Fahrsituation/en besonders typisch für einen Dieselmotor sind.

Versetzen Sie sich in folgende Situation :

Setzen Sie sich bitte in den Sitz der Versuchsplattform. Stellen Sie den Sitz so ein, dass Sie bequem sitzen (Verändern Sie dazu bitte nur die Entfernung zwischen dem Sitz und dem Lenkrad bei unveränderter Neigung der Rückenlehne). Fassen Sie das Lenkrad an den beiden Stellen an, die mit Klebeband gekennzeichnet sind. Stellen Sie zum Schluss Ihre Füße platt auf die Plattform (nicht auf die Fußrasten).

Stellen Sie sich vor, dass Sie am Steuer eines Autos sitzen. Die per Kopfhörer dargebotenen Geräusche und die Vibrationen von Sitz und Lenkrad erzeugen Empfindungen, die Sie im Inneren eines Wagens haben können. Sie entsprechen typischen Fahrsituationen, die Sie in Ortschaften oder außerhalb von Ortschaften antreffen können.

Ablauf des Experimentes :

Der Versuch hat zwei Abschnitte.

1. Versuchsabschnitt : Hören und Spüren
Ihnen werden einige Geräusche und Geräusche zusammen mit Vibrationen dargeboten, die Sie im Teil II beurteilen sollen. Jetzt besteht Ihre Aufgabe ausschließlich darin, die Geräusche und die Geräusche zusammen mit den Vibrationen anzuhören und zu spüren. Auf diese Weise bekommen Sie eine Vorstellung über die später zu beurteilenden Ereignisse.

2. Versuchsabschnitt : Hören, Spüren und Beurteilen
In diesem Versuchsabschnitt werden Ihnen die Geräuschabschnitte mit den Vibrationen wieder einzeln nacheinander dargeboten. Bei jedem Geräuschabschnitt mit den Vibrationen werden Sie gebeten ein Urteil abzugeben als Antwort auf die folgende Frage:

"In welchem Maße entspricht dieser Geräuschabschnitt mit den Vibrationen einer Fahrsituation, die typisch für einen Dieselmotor ist? In welchem Maße geben Ihnen die Geräusche und die Vibrationen das Gefühl, am Steuer eines Dieselfahrzeugs zu sitzen?"

Geben Sie Ihr Urteil auf einer Skala von 0-10 ab, wobei:
* 0 bedeutet: Sie finden, dass sich dieser Geräuschabschnitt mit den Vibrationen *überhaupt nicht wie* ein Dieselmotor anhört und anfühlt,
* 10 bedeutet: Sie finden, dass sich dieser Geräuschabschnitt mit den Vibrationen *genau wie* ein Dieselmotor anhört und anfühlt.

Bemerkung : Bitte richten Sie Ihre Aufmerksamkeit ausschließlich auf die dargebotenen Geräusche und Vibrationen und lassen Sie deren Stärke außer Acht, sowie die Tatsache, ob Sie sie mögen oder nicht.

Bemerkung : **Am Ende dieses Experimentes können wir uns einige Minuten über Ihre Eindrücke zum Versuch (Einfachheit, Schwierigkeit des Tests ...) austauschen.**

HERZLICHEN DANK FÜR IHRE TEILNAHME !!!

Appendix L

Source	**df**	**SS**	**MS**	F	p	R^2
P	32	10.248	0.320			7.16
M	1	3.100	3.100	44.105	0.0001	2.17
M x P	32	2.249	0.070			1.57
S	5	49.607	9.921	87.558	0.0001	34.67
S x P	160	18.130	0.113			12.67
V	2	9.483	4.741	49.265	0.0001	6.63
V x P	64	6.160	0.096			4.30
M x S	5	0.477	0.095	3.582	0.0043	0.34
M x S x P	160	4.258	0.027			2.98
M x V	2	0.381	0.191	8.874	0.0004	0.27
M x V x P	64	1.375	0.021			0.96
S x V	10	15.481	1.548	31.582	0.0001	10.82
S x V x P	320	15.685	0.049			10.97
M x S x V	10	0.086	0.009	0.436	0.928	0.06

Table 8.15: ANOVA table with P: French participants, M: modality (A and VA), S: driving situation, V: vehicle (3-, 4- or 6-cylinder car), SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
P	33	12.222	0.370			10.39
M	1	1.362	1.362	13.003	0.0010	1.16
M x P	33	3.457	0.105			2.94
S	5	32.207	6.441	56.893	0.0001	27.40
S x P	165	18.681	0.113			15.89
V	2	6.508	3.254	39.690	0.0001	5.54
V x P	66	5.411	0.082			4.60
M x S	5	0.347	0.069	2.506	0.0323	0.30
M x S x P	165	4.574	0.028			3.89
M x V	2	0.033	0.017	0.688	0.5061	0.03
M x V x P	66	1.592	0.024			1.35
S x V	10	9.015	0.902	18.129	0.0001	7.67
S x V x P	330	16.410	0.050			13.96
M x S x V	10	0.358	0.036	2.193	0.179	0.31

Table 8.16: ANOVA table with P: German participants, M: modality (A and VA), S: driving situation, V: vehicle (3-, 4- or 6-cylinder car), SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Source	**df**	**SS**	**MS**	F	p	R^2
P	1	1.022	1.022	2.958	0.902	0.39
M	1	4.299	4.299	48.969	0.0001	1.64
M x P	1	0.189	0.189	2.158	0.1466	0.07
S	5	80.816	16.163	142.703	0.0001	30.84
S x P	5	1.257	0.251	2.220	0.0520	0.48
V	2	15.738	7.869	88.415	0.0001	6.01
V x P	2	0.297	0.148	1.667	0.1928	0.11
M x S	5	0.631	0.126	4.644	0.0004	0.24
M x S x P	5	0.195	0.039	1.435	0.2112	0.08
M x V	2	0.163	0.082	3.577	0.0307	0.06
M x V x P	2	0.256	0.128	5.618	0.0046	0.10
S x V	10	23.549	2.355	47.691	0.0001	8.99
S x V x P	10	1.044	0.104	2.114	0.0216	0.40
M x S x V	10	0.127	0.013	0.701	0.7236	0.05
M x S x V x P	10	0.313	0.031	1.738	0.0689	0.12

Table 8.17: ANOVA table with P: group of participants (French and German), M: modality (A and VA), S: driving situation, V: vehicle (3-, 4- or 6-cylinder car), SS: sum of squares, MS: mean square, F: F-values, p: p-value, R^2: percentage of total variance accounted for each effect.

Appendix M

<u>Consigne du test perceptif</u>

<u>Jugements de dissemblance et de préférence</u>

<u>But de l'expérience :</u>
Cette expérience consiste à :
1- <u>évaluer la dissemblance</u> entre des paires d'évènements [A,B]
2- évaluer la préférence sur ces paires d'évènements.
Ces évènements sont des stimuli à la fois sonores et vibratoires.

<u>Mise en situation :</u>
Prenez place sur le siège du banc d'essai. Réglez le siège afin d'être confortablement installé (nous vous demandons de ne régler que la distance entre le siège et le volant et de ne pas modifier l'inclinaison du siège). Posez vos mains sur le volant <u>aux deux endroits indiqués par les deux marques de scotch (position des mains10h10)</u>. Enfin, posez vos pieds <u>à plat</u> sur la plateforme.

Imaginez-vous à l'intérieur d'une voiture. Les évènements (sonores&vibratoires) qui vont vous être présentés au niveau du casque, du volant et du siège, reproduisent des sensations que vous pouvez ressentir lorsque vous êtes à l'intérieur d'une voiture.

<u>Procédure à suivre pour réaliser un jugement de dissemblance et de préférence :</u>

Jouez les évènements A et B (sonores et vibratoires) grâce au bouton "Ecoute de [A,B]". Les deux événements se présentent donc par paire par ce bouton.

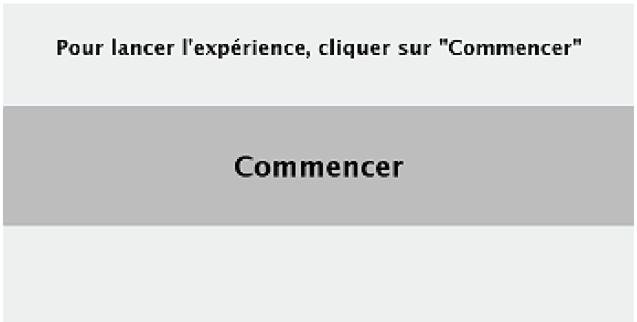
1- Vous devez en premier, juger la dissemblance (ou la similarité) entre ces deux évènements.
Le jugement se fait en déplaçant un curseur jaune entre le pôle «Très similaire» et le pôle «Très différent».

> Plus vous jugez que la différence entre les deux évènements est grande,
> plus vous devez déplacer le curseur près du pôle «Très différent».
> Inversement, plus vous jugez que les deux évènements sont similaires,
> plus vous devez déplacer le curseur près du pôle «Très similaire».

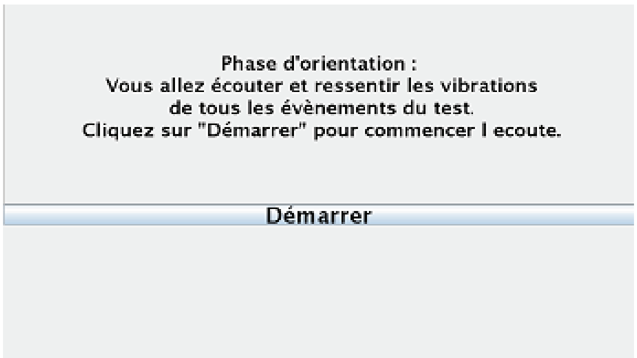
Vous ne pouvez pas rejouer la paire d'évènements "Ecoute de [A,B]. Soyez donc concentrés dès la première écoute et le plus instinctif possible dans vos évaluations.
Quand vous êtes satisfait de votre jugement de dissemblance par le curseur, vous pouvez passer au jugement de préférence en cliquant sur "Validez votre réponse";

Vous devez ensuite juger la préférence entre ces deux mêmes évènements. Vous ne pourrez pas les réécouter et effectuerez votre choix de préférence dans la foulée. Choisissez l'évènement que vous préférez en cliquant sur «Evènement A» ou «Evènement B». Quand vous êtes satisfait de votre jugement de préférence, cliquez sur "Validez votre réponse".

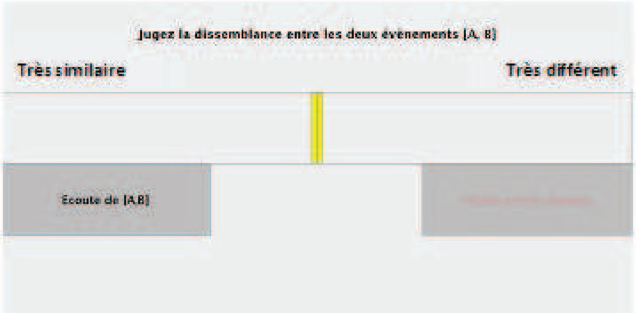
Déroulement global de l'expérience :
Pour commencer le test, appuyez sur « Commencer ».



Dans un premier temps, une phase d'orientation vous est proposée. Quelques évènements (sonores et vibratoires) de l'expérience vont vous être joués. Ceci vous permet de vous faire une idée du panel d'évènements que vous aurez à évaluer. Dans cette phase d'orientation, vous ne faites rien d'autre qu'écouter.



L'expérience proprement dite, consiste à effectuer 105 jugements de dissemblance et de préférence (105 paires à écouter). L'interface de dissemblance est celle représentée ci-dessous :



L'interface de préférence est celle représentée ci-dessous :

Remarque : Nous vous demandons de ne pas porter votre attention sur l'intensité de ces évènements ou sur des bruits parasites qui pourraient être présents, par exemple.

Contacter l'hôtesse une fois l'expérience terminée ou en cas de problème.

<u>Remarque :</u> A la fin de l'expérience, vous pourrez remplir un questionnaire pour parler de vos impressions sur le test.

MERCI DE VOTRE PARTICIPATION !!!

Il n'y a pas de mauvaises réponses, chaque réponse est une bonne réponse.

Appendix N

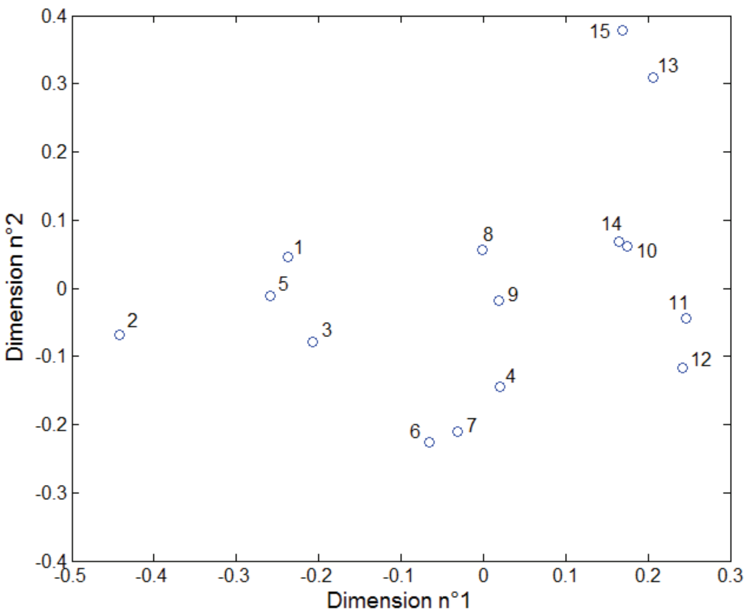


Figure 8.12: Representation of the perceptual *vibroacoustics* space obtained by the *CLASCAL* analysis for *acceleration* and for all participants. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

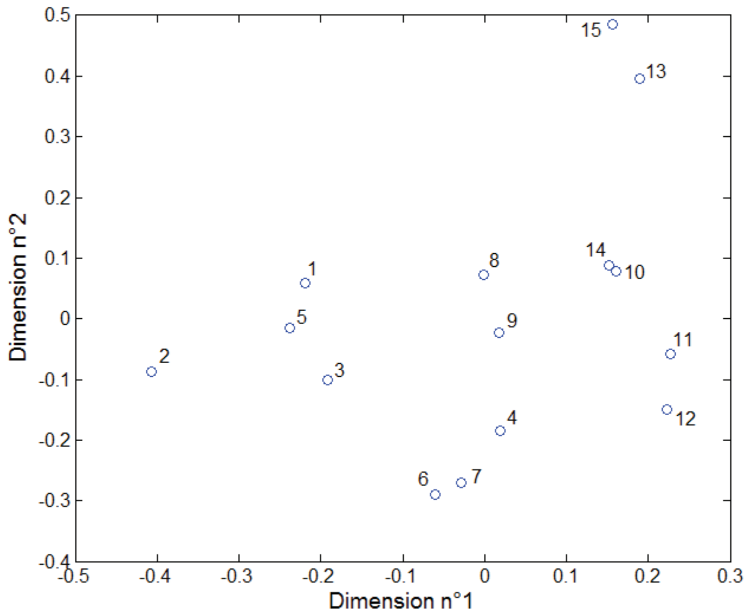


Figure 8.13: Representation of the perceptual *vibroacoustics* space obtained by the *CLASCAL* analysis for *acceleration* and for the 9 participants of the 2^{nd} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).

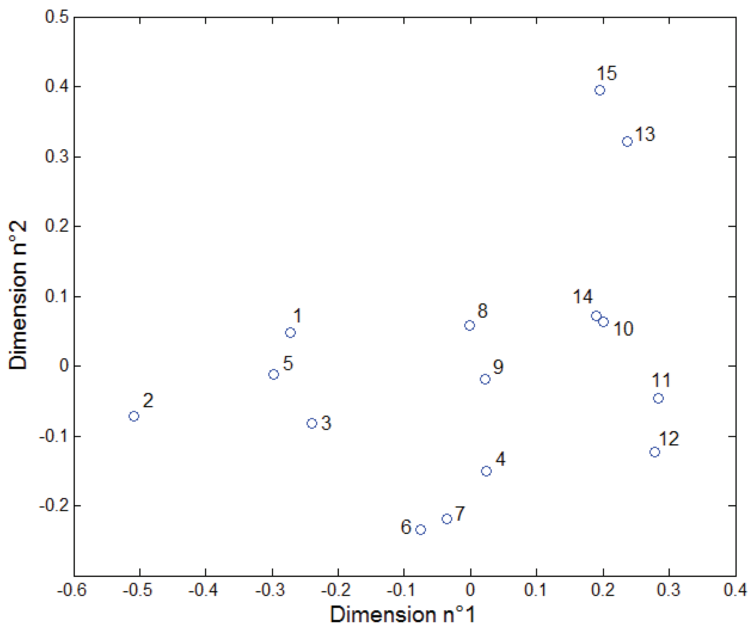


Figure 8.14: Representation of the perceptual *sound* space obtained by the *CLASCAL* analysis for *acceleration* and for the 16 participants of the 3^{rd} latent class. Each number corresponds to one vehicle: 1: Renault Laguna Coupé, 2: Hyundai Getz, 3: Peugeot 308, 4: Fiat 500, 5: Peugeot 407 Coupé, 6: VW Polo, 7: Hyundai I10, 8: Citroën C6, 9: Mercedes MC220, 10: Citroën C5, 11: Renault Mégane (filtered), 12: Renault Mégane (original), 13: Renault Mégane (the gasoline one), 14: Renault Grand Scenic and 15: Renault Grand Scenic (the gasoline one).