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Which driving situations best represent "the characteristic sound" of diesel engines?

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ABSTRACT

For several years, car manufacturers have significantly reduced the noise levels of diesel engines. This success brings a new challenge: how and in which driving situations is it possible to improve the sound quality of diesel engines in cars towards a higher customer appreciation. It is well established that the sound quality of gasoline engines is preferred to diesel engine sounds. The aim of this work, that focuses on the sound perception of diesel engines, is to explore positive characteristics of this type of engine sound in the listeners' mind. This paper presents the study in which we identified those driving situations where actually the typical diesel sound develops its proper characteristics. Typical driving situations (urban, rural, highway, etc.), for three different diesel engine classes (3, 4 and 6-cylinders) and different brands of cars are presented to listeners. Their task is to rate the dieselness of twelve sounds on an eleven-point scale. The results from this study, that help to improve the understanding of characteristic situations of diesel engine sounds, will be detailed and discussed in this article.

1. INTRODUCTION

The diesel engine has gone through a significant change that has enabled its increasing success on the automobile market in the past twenty years. From 25% in 1997, the market share of diesel vehicles in Europe has reached around 50% in 2005 and even 60% in France. The progress in the domain of acoustic noise diesel engines have promoted this strong breakthrough. A lot of studies have emerged from the scientific community on the understanding of the diesel engines noise perception. Especially, the combustion noise considered as the main defect of these engines, is extensively treated. Nowadays, this noise, that is better controlled, is often the topic of presentations of various international conferences related to the domain. However, the market conquered by this kind of motorization could risk, in the future, to suffer the impact of Euro 5 (2010) and Euro 6 (2014) regulations. Indeed, these new standards of exhaust emissions reduction, can directly impact the sound of diesel engines and can significantly damage the acoustic performances of these ones.

Nowadays, research focuses on the sound quality. In fact, marketing studies have shown that customers pay great attention to sound quality. As car manufacturers have realized that sound does influence the customer's satisfaction with the vehicle, research studies in sound quality became an essential part of product development[1]. It has become for car manufacturers, a major challenge.

2. PERCEPTION OF DIESEL SOUND

The sound of gasoline engines is preferred to this of diesel engines[2]. Its typical characteristic is an impulsive signal component with a periodicity defined by the cylinder firing[3]. Customers usually associate this diesel characteristic with negative features (“it sounds like a tractor”). However, thanks to improvements of sonority, performance, pollution, vibrations and other negative aspects of diesel, we are beginning to talk about "sound" of diesel engine and not only about "noise" of diesel engine. So, is it possible to identify positive attributes of the diesel sound engine? In order to focus on this question, a first step seems to be important: to extract one or some usual driving situations which are characteristic, for users, of diesel sounds. This article deals with the experiment realized in order to define which ones, among twelve different driving situations, could best represent the sound of diesel car.

3. LABORATORY TEST

A. Participants

34 participants (16 men and 18 women) who do not work in automobile or acoustics domains performed the test. Three criterions have been chosen for the recruitment of the participants. They had to:

- be devoid of hearing problems (but it was not checked with an audiogram),
- own a diesel car,
- drive often their diesel vehicle (daily or several times per week).

Each participant was paid for its participation. The average age of the participants is 44 years old.

B. Stimuli

For the present study, recordings have been realized in three different diesel cars (3-, 4-, 6-cylinders cars of inferior and middle range) on a same kind of road. The stimuli correspond to twelve various driving situations recorded with an artificial head at the co-driver position. Table 1 shows the wide range of these driving situations, which were assessed during the experiment. All of these situations can be encountered during a daily trip.

Table 1: *Twelve driving situations assessed by the participants of the experiment.*

Stabilized situations	Road signs	Unsteady situations	Road signs
hot idle		start up the motor	START UP THE MOTOR
constant speed 50-kph		stop the motor	STOP THE MOTOR
constant speed 70-kph		traffic light start	
constant speed 90-kph		acceleration	
constant speed 110-kph		deceleration	
constant speed 130-kph		traffic jam	

Moreover, Table 1 shows the correspondence between the road signs and the driving situations. Road signs used for each driving situation were chosen in cooperation with several colleagues of acoustics in order to validate their relevance according to French traffic law, describing the driver's expected behavior. Also, the participants had the possibility to chose a thirteenth image (“the sound does not correspond to any road sign”, cf Figure 2) if they did not succeed in finding the good road sign among the twelve of Table 1.

C. Apparatus

The experiment took place in a double - walled IAC sound - isolation booth in IRCAM, with a HPS IV amplifier system of Head Acoustics and a Sennheiser half-opened electrostatic headphone. This test lasted on average 48 minutes. At the end of the experiment, there was an interview to collect some information about their own cars and to know their impression on the test.

D. Methodology

The test is composed of three parts: orientation phase, identification phase and evaluation phase.

1. Orientation phase:

In the first part, the subjects listen to a sound sequence, composed of the different driving situations of Table 1. This part lasts around 5 minutes and allows them to understand which kind of sound they will have to rate in the third part.

2. Identification phase:

In the second part, the participants have to choose the road sign (cf Table 1) which, in their opinion, best corresponds to the sound that they have just heard.

3. Evaluation phase:

In the third part, each participant listens to the driving situations once again. We ask them to assess each sound on an eleven-point scale answering these following questions:

Up to what point does this sound correspond to a typical driving situation of a diesel car? In other words, up to what point does it call up a diesel sound? Up to what point does it allow to be aware of a diesel sound?

They evaluate each sound on an eleven-point scale from 0 to 10 such as:

- 0 means that they think the sound does not evoke the sound of a diesel engine at all,
- 10 means that they think the sound evokes the sound of a diesel engine perfectly.

Each participant performed these three parts twice in order to evaluate two different vehicles. In the following of this paper, we will speak about three parts and two steps of the experiment. Thus, the six possible configurations and the number of the people who performed the test with each configuration are brought back in Table 2.

Table 2: *The different configurations performed by the 34 participants.*

	Configurations					
Number of cylinders	3-4	4-3	3-6	6-3	4-6	6-4
Number of participants	6	6	6	5	5	6

Table 2 illustrates (e.g. in the first column of the configurations) the fact that six persons performed the experiment with the 3-cylinders car in the first step and the 4-cylinders car in the second step of the test. Therefore, 20 participants at least evaluated each vehicle and 10 for the same “position” (i.e. first or second listening).

4. RESULTS AND DISCUSSION

A. Identification of road signs

First results for the identification part of the test show that more than 85% of people (for the three different motorizations: 3-, 4- and 6-cylinders) have found the correct correspondence between the **start up the motor** and the **stop the motor** pictures with the sounds. This score can reach 100% for the 4-cylinders car. However, we can precise here that the road signs for these two driving situations are more explicit than the others. Indeed, only these two images which correspond to these driving situations do not result from the highway code (cf Table 1). The **hot idle** is the third driving situation and the first stabilized situation that participants recognized the best with an average of 72% of *correct choices*[*].

Figure 1 presents the results obtained for the *correct choice* of road signs. The y-axis represents the percentage of people who made the *correct choice* and the x-axis, the twelve driving situations of the test.

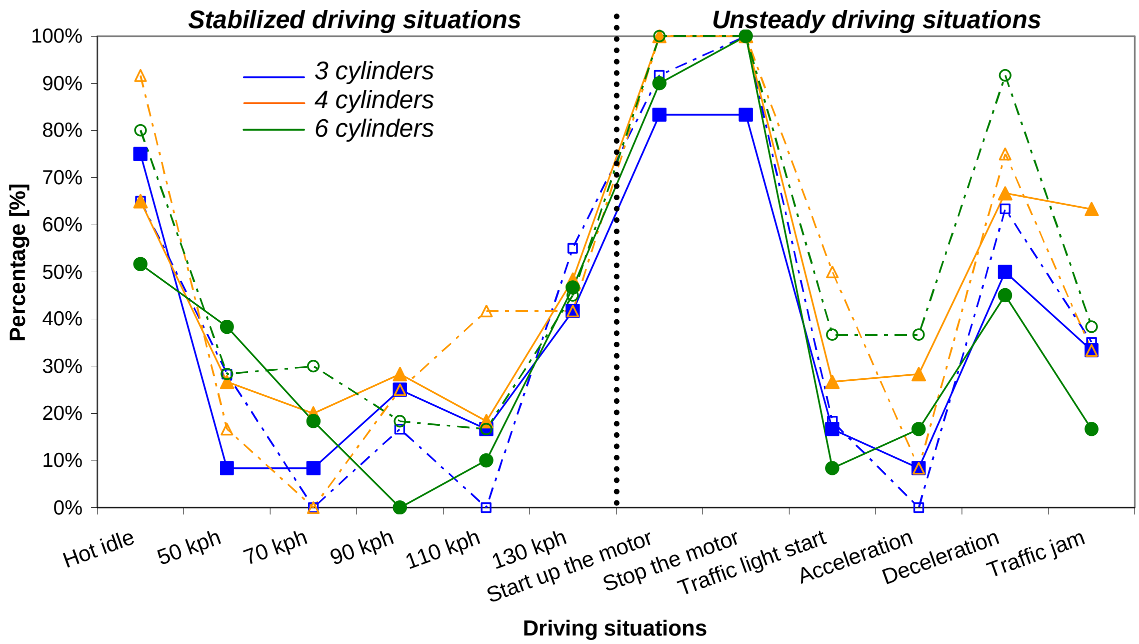

Figure 1: Proportion of participants who made the correct choice of road signs (1st step of the test with solid lines and 2nd step of the test with dashed lines).

For instance, the blue solid line represents the results obtained when the 3-cylinders car has been listened to at first during the experiment (configurations 3-4 and 3-6) and the blue dashed line represents when it has been listened to at last (configurations 4-3 and 6-3). The representation is the same for the 4- and 6-cylinders cars.

The first results of Figure 1 show that in the case of the stabilized driving situations, the choice of road signs for the 3- and 4-cylinders vehicles is not easier if the car is the second vehicle rated of the experiment. So, there are few effects of training for these two vehicles in the cases of stabilized situations. Nevertheless, this conclusion does not hold in the case of the 6-cylinders car.

However, for unsteady situations, the second step (dashed line) allows to have better results. The 4-cylinders vehicle presents its best results for the **start up the motor** and the **stop the motor** for each configuration, as already been said. We can see there is a decrease of *correct choices* for the **acceleration** (in the second step and for the 3- and 4-cylinders cars) with a difference of 8% (3-cylinders) and 20% (4-cylinders) regarding to results of the first step.

Concerning to the third car, when the 6-cylinders is heard in the second step of the experiment, the results obtained are better than when it has been heard in the first step of the experiment.

A statistical study, giving quantitative results about the effect of order of the configuration, should validate the first assumptions made about the results of the diagram.

[*] On the one hand, we are going to talk about correct choice of road sign, when the participant chose the same correspondence as the one given in the Table 1 between the sound and the image. On the other hand, we will talk about incorrect choice.

A remarkable point can be underlined still in this figure: the lowest results obtained (still for the unsteady situations), are for the **traffic light start** and the **acceleration**. We now focus on the *incorrect* answers made by the participants for this two particular driving situations, with a third one (the **stabilized 130-kph** sound) which can help to explain these *incorrect* answers.

Figure 2 presents the results obtained for the *incorrect choice* of road signs for three driving situations sounds (only for the 3-cylinders car). The y-axis represents the percentage of people who made the *incorrect choice* and the x-axis, the three driving situations on which we want to focus especially here: the sound that corresponds to a **traffic light start**, the **acceleration** and the **stabilized 130-kph**.

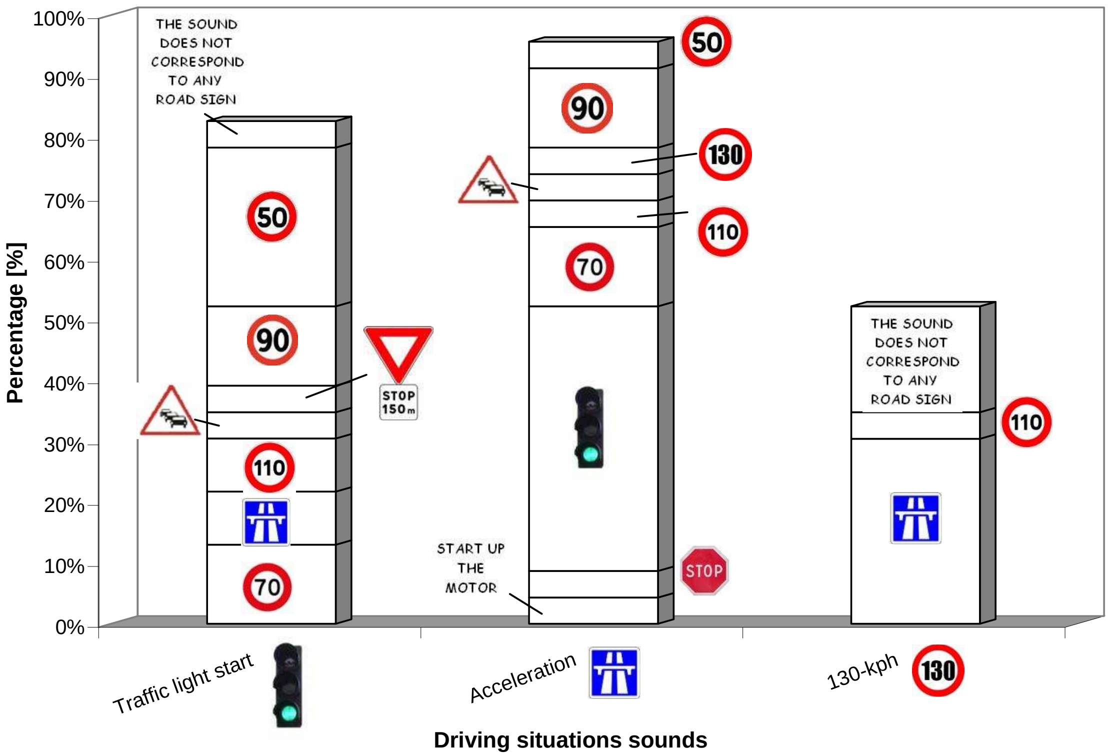

Figure 2: Proportion of participants who chose incorrect road signs for the traffic light start, the acceleration and the 130-kph sounds (for 3-cylinders car).

First, Figure 2 illustrates that eight different road signs have been used for this **traffic light start** sound. Most of them (up to 25%) chose the '50-kph' road sign. This answer is interesting because we can think that people assimilated the **traffic light start** sound to a driving in a city center (where French people must not drive above 50-kph). They could perhaps recognize a sound as a smooth acceleration but they may have thought about the driving situation where "they were going to arrive". Around 4% of the people chose the image "the sound does not correspond to any road sign" for the **traffic light start** sound.

For the **acceleration** sound, 43% of the subjects associated this **acceleration** to the 'traffic light start' sign. The reason could be found in the comparison of the two spectrograms in Figure 3 (the spectrogram of the **traffic light start** situation at the top and the spectrogram of the **acceleration** situation at the bottom). The other road signs ('start up the motor', 'stop', '110-kph', 'traffic jam', '130-kph' and '50-kph' from the bottom to the top of this figure) were chosen by less than 5% of the participants for the **acceleration** sound.

At last, 30% of the participants have chosen the blue highway road sign (cf Table 1 for the correspondence with the sound) with the **130-kph** sound. One possible explanation can be that the people recognized a high-stabilized speed which made them thought about the highway and then they chose this sign (the limited speed on a French highway is 130-kph).

17% of them did not succeed in recognizing the driving situation and chose the thirteenth image.

Figure 3 presents the spectrograms of the **traffic light start** and the **acceleration** sounds. The y-axis represents the frequency and the x-axis, the time in seconds.

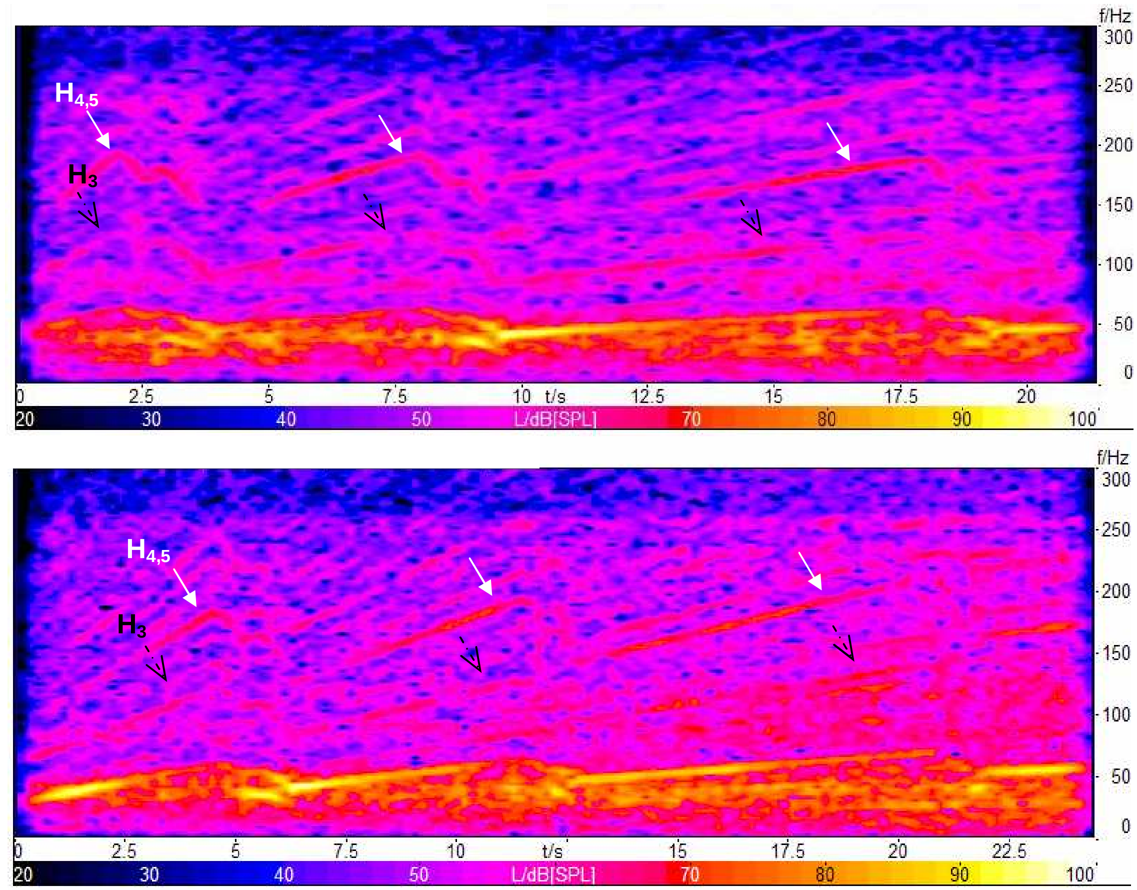

Figure 3: Spectrograms of the traffic light start (at the top) and the acceleration (at the bottom) driving situations (3-cylinders car).

The spectrograms of Figure 3 show that the emergence of the harmonic 4.5 (white arrows) in the same range of frequencies (around 200 Hz) for the two driving situations and the different changes of gear during these two situations.

This first part of the discussion dealt with some results of the identification phase (cf 3.D). We focused on the *correct choices* made by all the participants and for the different configurations (for the three cars, cf Figure 1) but other statistical studies will confirm or not, the effect of the context in these first results. In addition, we exposed some *incorrect choices* (just for the 3-cylinders car) for three driving situations. We can just notice that people do not understand the meaning of the road signs as we have decided to use them.
This part allows us to show that the **acceleration** and **traffic light start** spectrograms are very close, both having the harmonic 4.5 emerging more for the 3-cylinders car.

B. Dieselness evaluation

Dieselness evaluation was realized during the third and last part of the test. During this part, the participants had to evaluate the dieselness[4-5-6-7] of each driving situation answering these questions:

Up to what point does this sound correspond to a typical driving situation of a diesel car? In other words, up to what point does it call up a diesel sound? Up to what point does it allow to be aware of a diesel sound?
They evaluated each sound on an eleven-point scale from 0 to 10 such as:
- 0 means that they think the sound does not evoke the sound of a diesel engine at all,
- 10 means that they think the sound evokes the sound of a diesel engine perfectly.
Each of them has been presented to the subjects twice in a random order.

Figure 4 presents the mean values of the notes (for the 34 participants) and the standard deviation for each driving situation and for each listening order. The y-axis represents the normalized mean notes and the x-axis, the driving situations. For each one, the first column corresponds to the first listening and the second one to the second listening.

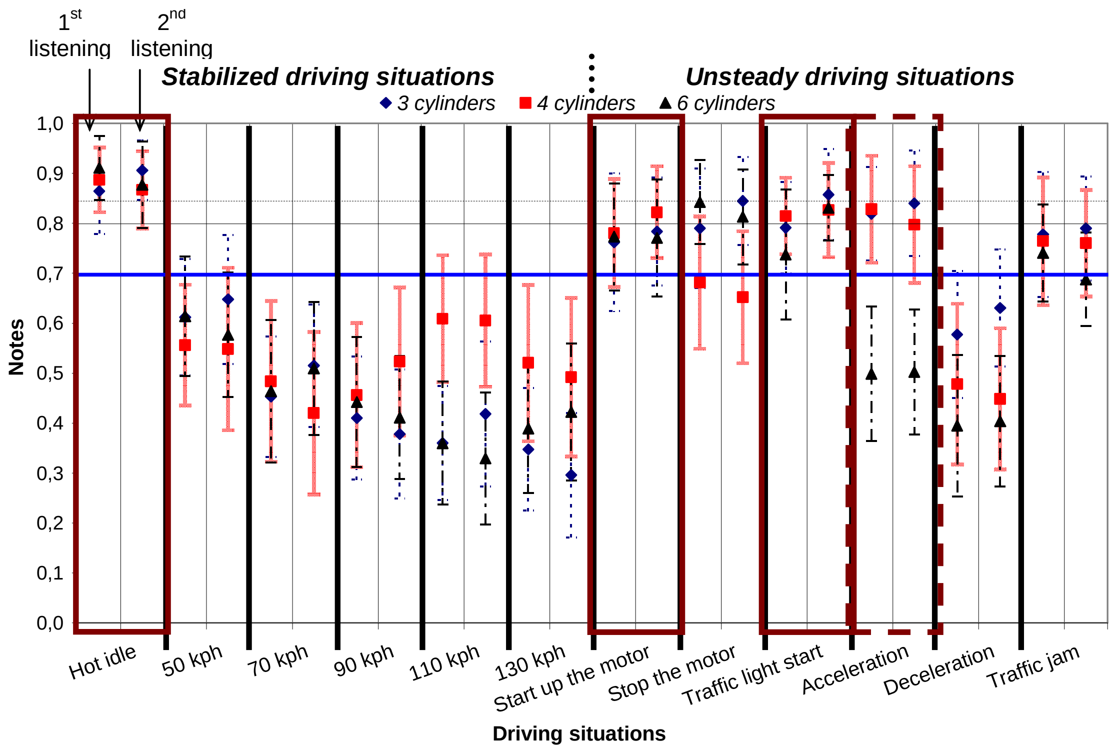

Figure 4: Mean notes given for each driving situation and for each listening.

In this figure, we can focus on the best results obtained. Indeed, the more one situation obtains a high note, the more the dieselness is perceived by the participants. First, the dashed line shows that the **hot idle** is perceived as the most characteristic driving situation, towards diesel sound, with 0.86 as the lowest note, obtained for the 3-cylinders and with 0.91 as the higher note (for 3- and 6-cylinders). The black solid line allows to see that the **start up the motor** is the second driving situation, which best represents the characteristic of the diesel sound for the three vehicles (with marks above 0.75). Last, with the blue solid line (note of 0.7), the **traffic light start** appears like the third driving situation the most characteristic of the diesel sound. All the **stabilized** driving situations and the **deceleration** obtained all their scores (for the three vehicles) below this last reference (0.7). For one particular unsteady driving situation (the **acceleration**), we have results more variable according to the number of cylinders. The 6-cylinders car obtains marks lower than for the 3- and the 4-cylinders with only 0.5 for each listening.
In this figure, we give the mean marks for the participants who assessed each car (23 participants for the 3- and 4- cylinders car and 22 for the 6-cylinders car). For instance, for the 3-cylinders car, the marks in each column are for the configurations 3/4, 4/3, 3/6 and 6-3. However, statistical study will allow to verify the influence of the context and the possibility to average the marks for all participants.

Table 3 shows the mean marks (for the two listenings) for six particular driving situations which obtained, at least for one vehicle, a note superior or equal to 0.7.

Table 3: *Driving situations with marks superior or equal to 0.7 (for at least one vehicle).*

	Mean marks		
Situations	**3-cylinders**	**4-cylinders**	**6-cylinders**
Hot idle	0.88	0.88	0.89
Start up the	0.77	0.80	0.77
Traffic light start	0.82	0.82	0.78
Traffic jam	0.78	0.76	0.71
Stop the motor	0.82	0.67	0.83
Acceleration	0.83	0.81	0.50

Table 3 presents in the first part (the first four driving situations), the driving situations that obtained mean marks superior or equal to 0.7 for the three vehicles. The second part of this table gives the scores of the two driving situations that obtained mean marks superior or equal to 0.7 for two vehicles only.

Figure 6 presents the notes obtained for the six driving situations of the Table 3. The y-axis represents the notes and the x-axis, the six driving situations. For instance, blue solid line represents the results obtained when the 3-cylinders car has been listened to at first during the experiment (configurations 3-4 and 3-6) and the blue dashed line represents when it has been listened to at last (configurations 4-3 and 6-3). The representation is the same for the 4- and 6-cylinders cars.

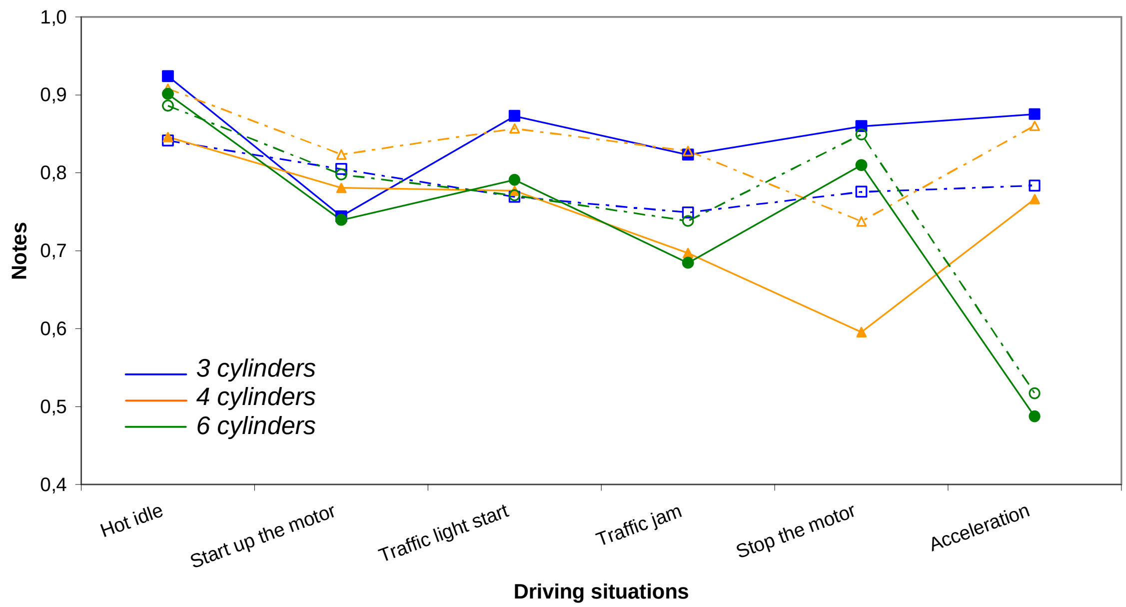

Figure 6: Notes given by the participants for the evaluation of the character of diesel sound (1st step of the test with solid lines and 2nd step of the test with dashed lines).

Figure 6 shows that in the case of the 3-cylinders car and for five driving situations on the six presented here, the marks given, when this vehicle is evaluated in the second part of the experiment (dashed line), are not better than in the first part (solid line). For the 4- and 6-cylinders cars, the results are different because the dashed lines present, in general, better results than the solid lines. Thus, there is an influence of the configuration for the rating of the sounds; a positive influence for the 4- and 6-cylinders cars and a negative influence in the case of the 3-cylinders. The same statistical studies (we have already spoken about in Figure 1) will help us to conclude more precisely about the importance of the context.

After having discussed about the mean marks given for each listening of driving situations, Table 4 summarizes the results of the driving situations which best represent the dieselness of each car.

Table 4: *The typical diesel driving situations.*

3 cylinders	4 cylinders	6 cylinders
1. Hot idle 2. Acceleration 3. Traffic light start / Stop**	1. Hot idle 2. Traffic light start 3. Acceleration 4. Start up***	1. Hot idle 2. Stop** 3. Traffic light start 4. Start up***

Table 4 illustrates that the **hot idle** is unquestionably the driving situation that best represents the diesel sound for each car. The **traffic light start** appears also for the three cars in the second or in the third position. For the 3- and the 4-cylinders cars, the **acceleration** and the **traffic light start** share the second and the third place in the bottom of the table. We spoke about the two driving situations in **4.A** that these two situations are similar because the results of these recordings are acceleration (smooth or not). Therefore, an **acceleration**-driving situation seems to be characteristic of the dieselness too.

5. CONCLUSION

This article exposed the results of a listening test in order to highlight some driving situations that best characterize the diesel sound. This experiment allowed to assess twelve different driving situations for three vehicles (3-, 4- and 6-cylinders cars).

The first part of the test (orientation phase) was a 'technical' part to allow participants to listen to the range of sounds, they would have to evaluate. The second part allowed to make sure of the right interpretation of a driving situation sound with the road sign. However, we tested some methodology with the association between an image and a sound. The results showed that the choices for the **stabilized** sounds did not have *correct* results. The discrimination between the different speeds (**50-kph** to **130-kph**) is not an easy exercise. Concerning the **unsteady** situations, **traffic light start** and **acceleration** collected more *incorrect choices* for the recognition of the road signs (for the 3-cylinders car). We explained these *incorrect* answers in Figures 2 and 3, with a confusion of meaning for the blue highway road sign (which represents an acceleration for us, whereas for the participants, it represents more a stabilized 130-kph situation).
At last, the third part of the experiment could answer the goal of this one: which driving situations best represent "the characteristic sound" of diesel engines? The results showed that **hot idle** and **acceleration** / **traffic light start** best represent "the characteristic sound" of diesel engines.
The results of this experiment allow us to choose these two driving situations (**hot idle** and **acceleration** more or less smooth) for the following of the study about the sound perception of diesel engines. Two other steps will be studied in the future:
- the comparison of these results with those of the same test realized in Germany,
- the research of positive attributes of these driving situations.

** Stop the motor
*** Start up the motor

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