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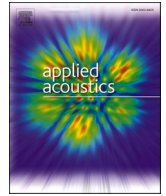
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External tire noise: Determination of timbre parameters and unpleasantness factors, with a focus on truck tires

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ABSTRACT

The Leon-T project aims to reduce emissions (noise and particles) from heavy goods vehicles (HGV) tires. This study was focused on the noise emitted by tires in suburban conditions (70 km/h). Its aim was to identify the sound parameters responsible for the unpleasantness of this noise. An initial experiment based on recordings (of passenger cars, light and heavy goods vehicles) highlighted the important timbre parameters used by listeners in two conditions (signals recorded at the roadside and modified to simulate the effect of a standard facade). For noises heard inside dwellings, it seems that intensity and tonality are the most important factors (unlike car tires, truck tires can emit noise with a strong tonal character). In a second experiment, signals were synthesised to simulate tire passing noises, with controlled loudness and tonality. Participants were asked to evaluate the unpleasantness of sounds. Results showed that the contributions of both factors to unpleasantness were equivalent. This could lead to the recommendation that tonality be considered in of tire noise regulations.

1. Introduction

Road transport is a major cause of annoyance in urban and semi-urban areas. In such an environment, given the limited speed of vehicles (below 80 km/h), aerodynamic noise is negligible. Moreover, the new electric engines are very quiet [1]. Tire noise is therefore becoming the main source of vehicle noise in such environments.

The regulation for pass-by noise [2] consists of imposing a maximum value for the A-weighted sound level as measured when the vehicle passes in front of a microphone with the engine switched off. However, it is known that, in many other cases, sound timbre parameters can contribute to the annoyance or discomfort. As an example, it has been shown that sharpness, tonality and roughness significantly contribute to the annoyance of accelerating vehicles [3]. To our knowledge, similar studies focusing on tire noise alone are very rare. In the case of interior passenger cars, Buss et al. [4] collected the terms used to describe tire noises by professional drivers at a tire manufacturer. Six main categories emerged: Drumming, Pattern noise, Booming, Rumbling, White noise and Growling/Grinding. Using a smaller set of tires, Franck et al. [5] identified three main dimensions (loudness, spectral balance and tonal component). More recently, Bekke et al. [6] proposed a simple model of tire noise as heard inside the vehicle, allowing to control loudness,

tonality and drumming noise of such stimuli (drumming noise being related to amplitude modulation). A listening test experiment gave indications of the relative influence of each factor on the sound quality. For exterior tire noise, there are even fewer studies. Hoffmann et al. [7] have shown that, in the case of three different tires, listeners can perceive significant differences in sharpness and roughness. It should also be mentioned that all these studies concerned passenger cars. In the case of van or truck tires, no publication reporting a similar study could be identified - whereas the tires can be very different from those used in passenger cars.

The aim of the studies described in this article is therefore to fill this gap and to identify the main sound parameters of tire noise of a passing vehicle (either passenger car, van or truck). In order to remain in a configuration close to that used by the regulations, the pavement is fixed and respects the recommendations of the ISO 10844: 2021 standard [8]. On the other hand, tires were of different categories (C1 to C3). As road transport noise is particularly annoying for nearby residents, the perceptual space of tire noises was determined under two conditions: (1) from recordings made outdoors (7.5 m from vehicles' passing line) and (2) after filtering these signals to simulate the attenuation of a standard residential building facade. In both cases, a free sorting experiment was conducted, in order to identify the key characteristics of sounds. In the

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case of indoor sounds, the study went on to investigate the influence of these prominent parameters on the short-term unpleasantness described by the listeners.

2. Experiment 1: Identification of tire noise timbre parameters

2.1. Material and methods

2.1.1. Sound stimuli

2.1.1.1. Exterior listening condition. The sound stimuli were taken from the set of recordings made by Applus + IDIADA on a recording track compliant with the requirements of ISO 10844:2014 which specifies the characteristics of the test surface intended to be used for measuring tire noise emissions.

A free field microphone (Brüel&Kjaer, Model 4966) equipped with a windscreen, linked to an acquisition system (SQuadriga II, Head Acoustics) and calibrated with a Brüel&Kjaer Model 4231 was used. The microphone was located 7.5 m from the center of the track and 1.2 m above the ground. The vehicle speed was measured with a GPS located inside the vehicle (Racelogic VBOX). Photoelectric sensors were located 15 m before the microphone to detect the passing of the front of the vehicle. When the sensors detected the vehicle, they sent a trigger to the acquisition system which allows to start simultaneous measurements of noise and vehicle speed. This procedure was compliant with the UN/ECE Regulation R117 [9], which defines tire noise measurements.

All vehicles were recorded with an initial speed of 70 kph when passing in front of the photoelectric sensors. Measurements were carried out in a coast-down condition (engine off and gear box at neutral position) or with the engine on. Sound was recorded until the vehicle was 15 m after the microphone. As the distance travelled by the vehicle was 30 m, the stimuli duration was 1.54 s. Three type of vehicles were used: a sedan passenger car (using C1 tires), a van (C2 tires) and a heavy truck (C3 tires). Each vehicle was equipped with different sets of tires. In the case of trucks, it is common practice not to fit the same type of tire at the front (steering tires) and at the rear wheels (traction tires). However, in this experiment, the same type of tire was used for all wheels. Furthermore, as vehicles had conventional (IC) engines, some passing were realized with the engine running, in order to know the influence of engine noise. The resulting dataset was composed of 33 recordings (see Table 1). The maximum A-weighted sound pressure level of these recordings ranged from 67.5 dB(A) to 80 dB(A).

2.1.1.2. Interior listening condition. The recordings can be used to represent an exterior condition (what a pedestrian can listen). In order to simulate a condition in which the listener is at home, with closed windows, some modifications had to be applied to the stimuli. Using a software specialized in building acoustics [10], the isolation of a facade was computed. The facade had the following properties: a 10 cm thick concrete wall (21.32 m²) and a double-glazing window (1.44 m²), equipped with an air intake and a rolling shutter box. This represents a configuration that can be found throughout Europe while allowing for a Weighted Sound Reduction Index $R_w = 43$ dB (Fig. 1), which satisfies all the current minimum regulations regarding outdoor noise in Europe [11].

The software computes the apparent sound insulation index R in dB (SPL) for frequencies ranging from 50 Hz to 5000 Hz. R is the difference between the incident sound power level (L_{pi}) and the transmitted one (L_{pt}).

This can be converted as

$$P_t = P_i \cdot 10^{\frac{-R}{20}} \tag{1}$$

Where P_i represents the incident sound pressure and P_t the transmitted one. Thus, the quantity $10^{\frac{-R}{20}}$ can be considered as the frequency response of a filter which can be used to modify the exterior noise.

Table 1

Characteristics of the recordings. The first column gives the tire class (C 1: passenger car, C2: light truck, C3: heavy truck). The second column indicates the tire dimensions. The third one gives the type of the tires (traction/steering) in the case of C3 tires only. The last column indicates if the engine was turned on or off during the recording.

Type	Tire dimensions	Usage	Engine
C1	225/55 R17	N/A	On
C1	225/55 R17	N/A	Off
C1	225/55 R17	N/A	Off
C1	225/55 R17	N/A	On
C2	235/65 R16C	N/A	Off
C2	235/65 R16C	N/A	On
C2	235/65 R16C	N/A	Off
C2	235/65 R16C	N/A	On
C3	285/70 R19.5	Steering	Off
C3	315/80 R22.5	Steering	Off
C3	315/80 R22.5	Traction	Off
C3	315/80 R22.5	Traction	Off
C3	315/80 R22.5	Steering	Off
C3	315/80 R22.5	Steering	Off
C3	315/80 R22.5	Steering	On
C3	315/80 R22.5	Traction	On
C3	315/80 R22.5	Traction	Off
C3	315/80 R22.5	Traction	On
C3	315/80 R22.5	Steering	On
C3	285/70 R19.5	Steering	On
C3	285/70 R19.5	Traction	On
C3	315/80 R22.5	Steering	Off

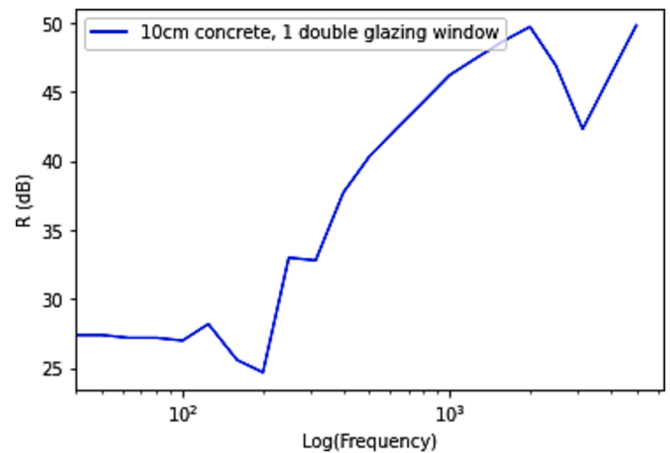


Fig. 1. Frequency response of the filter for each 1/3 octave.

Using the frequency response (Fig. 1), the finite impulse response (FIR) filter of the corresponding was calculated with python 3.9.7 [12] and SciPy [13]. The length of the impulse response was fixed to 40,000 samples. Thirty-three sounds were then obtained by application of this filtering to the outdoor recordings. The global level of sounds ranged from 26.7 dB(A) to 39 dB(A), which corresponds to relatively quiet levels observed at nights but that would still elicit some sleep disturbance [14].

In total, two sets of 33 recordings were prepared (exterior condition / interior condition). Stimuli were recorded as 16-bits wav files (sampling frequency: 44100 Hz). In each condition, the perceptual space of sounds was determined using a free sorting task experiment.

2.1.2. Participants

Fifty-three students (18 women, 35 men) participated in the listening test. They were between 19 and 27 years old (mean age: 21.17 ± 1.78 years). The experiment took place in a large sound proof booth (3.4 m long, 2.4 m large and 2.2 m high) in which a participant can feel

comfortable. A window allowed to monitor the progress of the experiment and to check that the participant was doing well. At the start of the experiment, the hearing threshold of each participant was measured according to the ISO 8253-1:1989 standard (tonal audiometry, 7 frequencies between 125 and 8000 Hz). The procedure used the Eolys Piston XP software (on a Dell optiplex 9020 computer) and 3 M PELTOR Optime II headphones. Measurements showed that all participants had normal hearing (i.e. their hearing threshold was below 20 dB HL at all tested frequencies).

Sound stimuli were presented through headphones (Sennheiser HD650). Levels ranged between 67.7 and 80 dB(A) in the exterior condition, between 27 and 39 dB(A) in the interior condition). Due to the very short duration of stimuli, the sound exposure did not last more than 30 min, which avoided any risk of hearing damage to the participants.

2.1.3. Free sorting task protocol

For each condition (exterior and interior), the participants had to sort the sounds according to their similarity. Their task was to create groups of similar sounds. They could make as many groups as they wanted and could listen to each sound as many times as needed.

Sounds were played by a USB audio interface (RME Fireface UC) linked to high quality headphones (Sennheiser HD650). The free sorting task, used a graphical interface developed in-house (using Python [11] and tkinter [15]). Each sound was represented by a number. Clicking on a number allowed the participant to listen to the corresponding sound. The participant could drag the numbers on the screen to define the groups. Fig. 2 shows an example of the screen after one participant achieved that task. When the first sorting task was completed, the participant had to repeat the task for the other listening condition. The order of the two listening conditions and also the attribution of the sounds to each number in each particular condition were randomized. All in all, the duration of the experiment was between 10 and 45 min (with an average of 20 min) and lower than 30 min for all participants but 9.

The experimental protocol (as well as the one used in the following experiment related in that paper) was approved by the Ethics Committee of Lyon University (Comité d’Ethique de l’Université de Lyon) under the number 2022-05-19-001.

2.1.4. Results

At the end of the experiments, individual co-occurrence matrices were built from the participants’ results for each condition. The matrices were

calculated using the following rule: if the participant grouped two noises together, then the value in the matrix for this pair is 0, if the noises were in different groups, the value is 1. We then obtained 53 triangular matrices in each condition. Individual matrices were averaged per condition, resulting in two mean matrices, whose values can be considered as distances between sounds (0 indicating that all participants considered the two sounds as being similar, 1 indicating that all participants considered these sounds should belong to different groups).

The two mean co-occurrence matrices were used as distance matrices to perform hierarchical agglomerative clustering [16] in R version 4.1.2 [17], an algorithm that organizes data into groups (clusters) by merging them according to their similarity using the mean euclidian distance aggregation criterion: the mean distance between the data inside a group is compared with the mean distance between the data in this group and data outside this particular group. This resulted into classification trees. In our case, the more often the noises were grouped together by the participants, the more likely they belong to the same cluster. The number of clusters is determined by cutting the tree at a given height. This height was selected using the maximum mean silhouette criterion [18] for each possible cut of the tree. This silhouette criterion ranges from -1 (all clusters are poorly separated) to 1 (all clusters are well defined and homogenous).

2.1.5. Selected psychoacoustic parameters

Different psychoacoustics parameters were computed with Artemis 13.2 (Head acoustics) in order to identify the common features of sounds within a same group:

- loudness (in Sone), computed according to the American ANSI S3.4-2007 standard [19], defined by Glasberg & Moore in 2006 [20] with the following parameters (soundfield: free, window length: 1024 samples, window type: Hanning, 50 % overlap);
- sharpness (in Acum) is related to the balance between high frequencies and low frequencies. The method described by von Bismarck with the standard ANSI S3.4-2007 [19] was used with the following parameters (soundfield: free, window length: 1024 samples, window type: Hanning, 50 % overlap);
- Roughness (in Asper) can be induced by modulation amplitude of sounds. It was computed according to the first edition of ECMA-418-2 [21];
- Tonality (in tuHMS) represents the audibility of one or several tones in the noise. The ECMA-74 procedure proposed was used (see Appendix G of ECMA-74 15th edition [22];

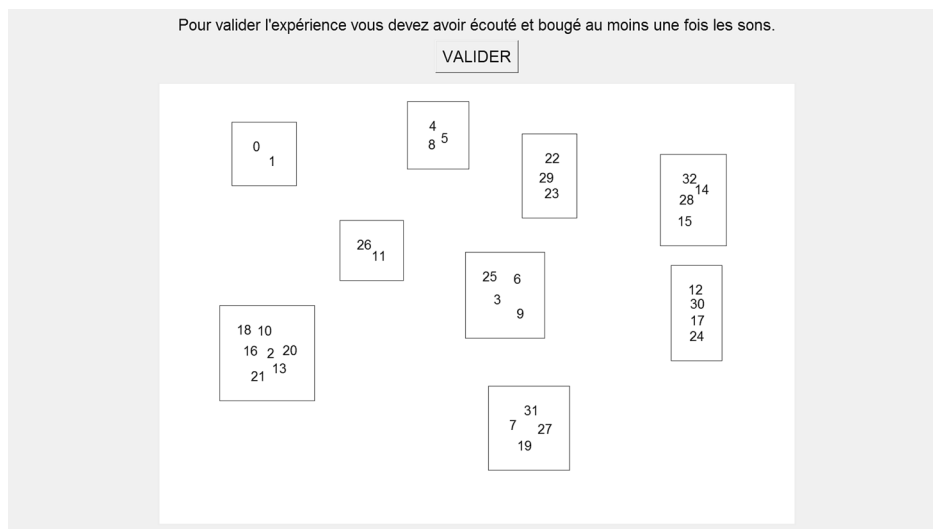


Fig. 2. An achieved sorting task. The different sounds are grouped according to the black rectangles. The participant could move each number freely and listened to the corresponding noise by clicking on it. To validate the task, each sound had to be moved and listened to at least once.

- Frequency of the lowest emerging tone (if any), using the specific tonality, i.e. the tonality calculated for each frequency;
- spectral centroid (in Hz) is the center of mass, i.e. weighted mean, of the frequency spectrum, in dBA.

The relevance of these parameters was confirmed by the free descriptions of sounds participants made informally after the experiment: the participants used criteria that were closely related or analogous to the ones these metrics are supposed to describe.

For each psychoacoustic parameter, non-parametric statistical analyses (Kruskal-Wallis or Wilcoxon) were used to assess the relevance of any differences that might appear between the groups of stimuli formed at the end of the free sorting experiment.

2.2. Results

The maximum silhouette criterion was obtained when cutting the tree in 5 clusters for the exterior condition and 2 clusters for the interior condition (Fig. 3). In the “exterior condition”, the number of stimuli in each group varied between 3 and 17. In the “interior condition”, the numbers were more balanced (13 and 20 stimuli).

In the “exterior condition”, Fig. 4 shows the boxplots of computed metrics in each group. There are important differences in loudness, roughness and tonality. Some of these differences can be related to the type of tire or the experimental condition:

- tonality is almost zero for group (4), which includes all stimuli using C1 and C2 tires (as well as some non-driven C3 tires). It is known that, for C1 and C2 tires (i.e. tires for cars or vans), manufacturers are aware of reducing tonality thanks to an adapted tread design.
- Loudest stimuli can be found in groups (2), 3 and 5, which are composed of C3 tires only. As these tires are larger than C1 and C2 ones, one can expect that they are noisier. In the first two ones are found C3 driven tires, which are known to be noisy.
- Recordings of C3 tires made with the engine running can be found in group (5). For some of them, the engine can be heard, which explains the large range of loudness and tonality values, as well as the low frequency of the most prominent tone.

In the case of the “interior condition”, two groups only could be built.

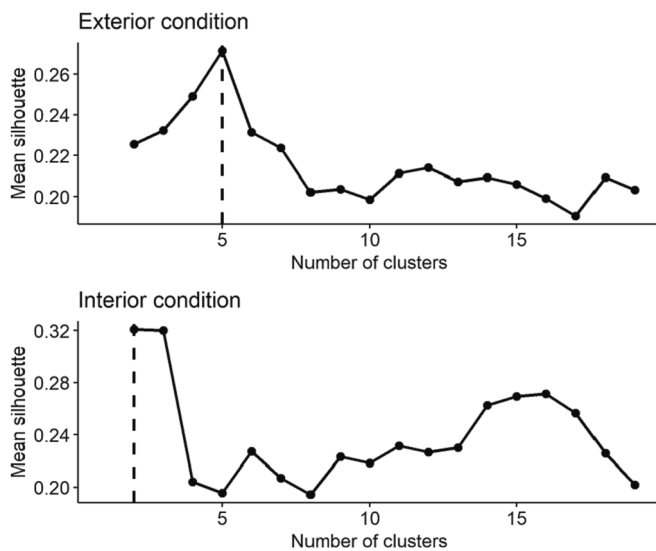


Fig. 3. Selection of the ideal number of clusters (highlighted by a dashed vertical line) according to the mean silhouette criterion according to the different number of clusters for each listening condition. The clusters are obtained by cutting the classification tree in different places.

The second group roughly corresponds to the fourth group of the “exterior condition”. Sounds from groups (1), 2, 3 and 5 in the “exterior condition” can be found in group (1) after the facade filtering. Thus, the first group is composed of C3 tires only and the second is a mix of C1, C2 and steering C3 tires.

The two groups mostly differ by their loudness and tonality (Fig. 5), which has highest values for sounds of group (1). The tonality is close to 0 for sounds in group (2). Even if statistically significant differences can be found between the two groups for roughness and sharpness, the differences are small and less easily detected when listening.

3. Experiment 2: Perceptual and psychoacoustical response to artificial tire sound stimuli

3.1. Material and methods

The results presented in the previous experiment showed that loudness and tonality are the key factors used by listeners when assessing the similarity of tire noises when heard inside a dwelling. This second experiment aimed at evaluating the influence of these factors on the unpleasantness of sounds. The experiment consisted in synthesizing sounds with four controlled parameters. One factor was the sound pressure level, related to loudness. The three other factors were related to tonality:

- Tonality factor (TF) was defined as the ratio between the amplitude of the tonal part of the sound and that of the noisy part;
- Fundamental frequency (F) is the fundamental frequency of the tonal part (if present);
- Bandwidth (Bw) is the bandwidth of each tonal component. Indeed, the analysis of the recorded stimuli showed that this can vary among passing-by noises.

The levels of these factors have been set on the basis of analyses of the recorded sounds, in order to represent the range of values measured from real tires.

3.1.1. A simple synthesis of tire noise

For a given combination of fundamental frequency (F), bandwidth (Bw) and tonality factor (TF), a stimulus was synthesized as the mix of a noisy part and a tonal part according to (Eq. (2):

$$\text{Stimuli}_{F,TF,Bw} = (1 - TF) \times \text{Noisy part} + TF \times \text{Tonal part}_{F,Bw} \quad (2)$$

The noisy part was generated using three low-pass filtered white noises added together as shown in (Eq. (3):

$$\text{Noisy part} = \text{Noise}_{2000} + 0.35 \times \text{Noise}_{20} + 0.2 \times \text{Noise}_{450} \quad (3)$$

In which: Noise_{2000} is a white noise filtered by a Butterworth lowpass filter ($f_c = 2000$ Hz, order 2). Noise_{20} is a white noise filtered by a Butterworth lowpass filter ($f_c = 20$ Hz, order 10), Noise_{450} is a white noise filtered by a Butterworth lowpass filter ($f_c = 450$ Hz, order 6). The resulting noise gives a reasonably good spectral approximation of the mean spectrum of the recorded coast down noises of C3 tires (Fig. 6).

To simulate the small random amplitude variations which can be observed in recordings, the amplitude of the noisy part was modulated as follows: 10 points equally spaced in time were generated using a random variable with a standard normal distribution (limited between -1 and 1). Then a cubic spline extrapolation was applied to generate the value of the modulation for the entire duration of the sound (Fig. 7). Each sample of the noisy part $\text{Noisy}(t)$, was multiplied by the corresponding modulation factor $\text{Mod}(t)$ following (Eq. (4):

$$\text{Noisy}(t) = \text{Noisy}(t) \times (1 + 0.05 \times \text{Mod}(t)) \quad (4)$$

Finally, the modulated noisy part is normalized so that its root mean

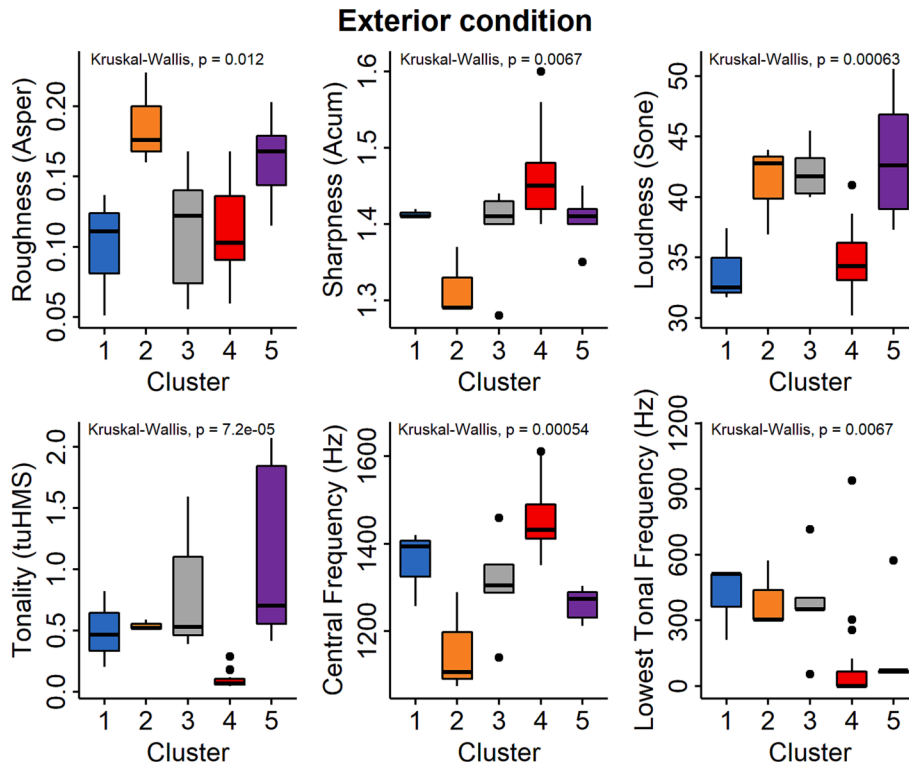


Fig. 4. Values of several psychoacoustics parameters in each cluster (exterior listening condition). The p-values on top of each boxplot are the result of a non-parametric ANOVA (Kruskal-Wallis test) to test the main of each parameter, i.e. it indicates that each parameter is affected by the cluster.

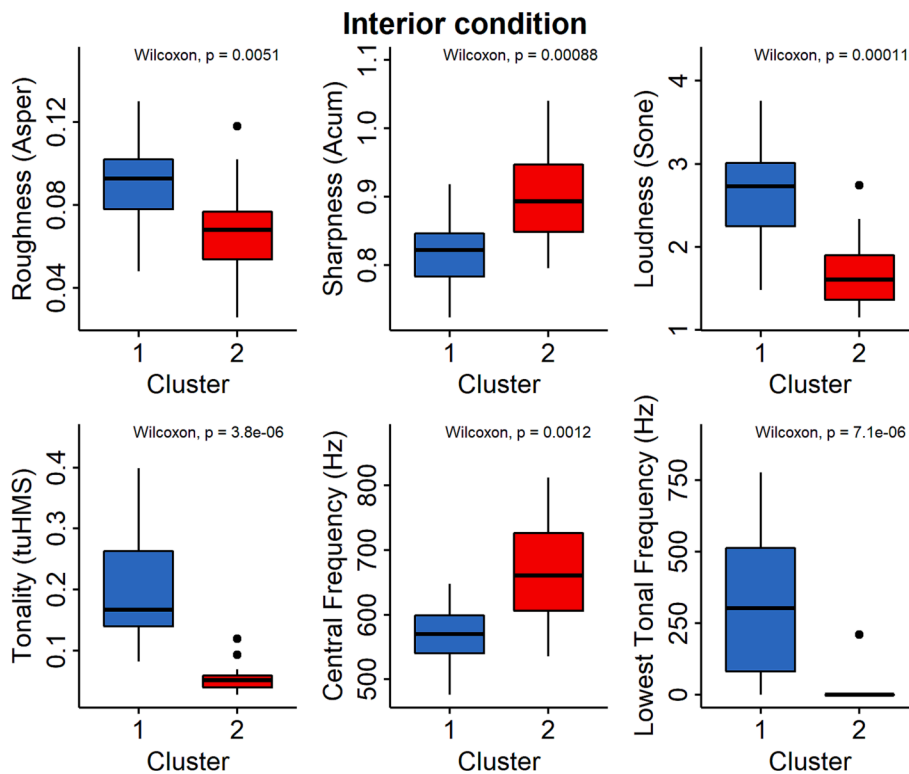


Fig. 5. Values of several psychoacoustics parameters in each cluster (interior listening condition). The values on top of each boxplot are the result of a non-parametric comparison test (Wilcoxon test) and indicates that each parameter is different between the two clusters.

square value is equal to 1.

Due to very slight variations of speed and the irregular patterns of tires, tonality of a tire noise is closer to a very narrow band of noise than

to a pure tone. White noises were filtered with FIR filters (length = 22001), with a frequency response made of sums of gaussian distributions, each of them being defined by a center frequency f_c and a

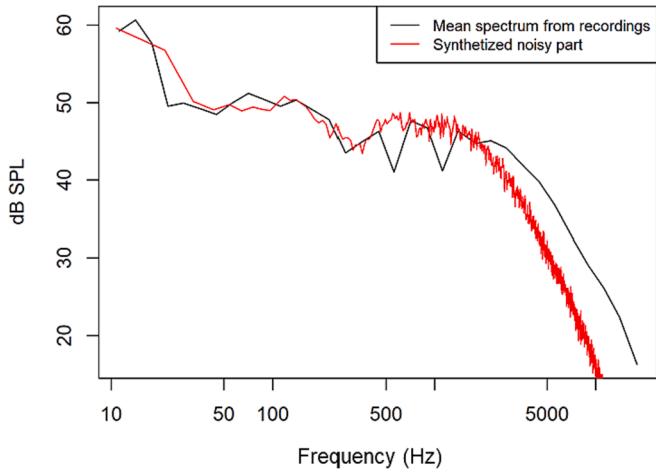


Fig. 6. Comparison of the spectra of the synthesized noisy part with the mean 3rd octave spectra of the atonal (noisy) part of the coastdown recording of HGV tires (C3) by IDIADA (window type: Hanning, window length: 4096 samples, overlap: 90%).

bandwidth Bw . The frequency response of each filter can be written as (Eq. (5)).

$$H(f, f_c, Bw) = \frac{1}{Bw\sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{f-f_c}{Bw} \right)^2} \quad (5)$$

Different spectra were constructed using 2 different fundamental frequencies ($F_0 = 300$ Hz or 500 Hz) with two harmonics for each fundamental, the level decreasing linearly between the harmonics. In addition, two different bandwidths ($Bw = 10$ or 25) were used to define the gain of the filter (Eq. (6), Fig. 8):

$$H(f) = H(f, F, Bw) + 0.5 \times H(f, 2F, Bw) + 0.25 \times H(f, 3F, Bw) \quad (6)$$

The values used for Bw roughly corresponds to frequency intervals equal to $[F - 8$ Hz; $F + 8$ Hz] for $Bw = 10$ and $[F - 20$ Hz; $F + 20$ Hz] for $Bw = 25$. As with the noisy part, the root-mean-squared value of the tonal part was also fixed to 1. Then, the noisy part and the tonal one were added together (Eq. (6), for a given tonality factor.

As a final step, two modifications were applied to the sound in order to represent the displacement of the vehicle: a Doppler effect and a modification of the amplitude. The Doppler effect was created by interpolating the synthesized noise along the evolution of the duration of

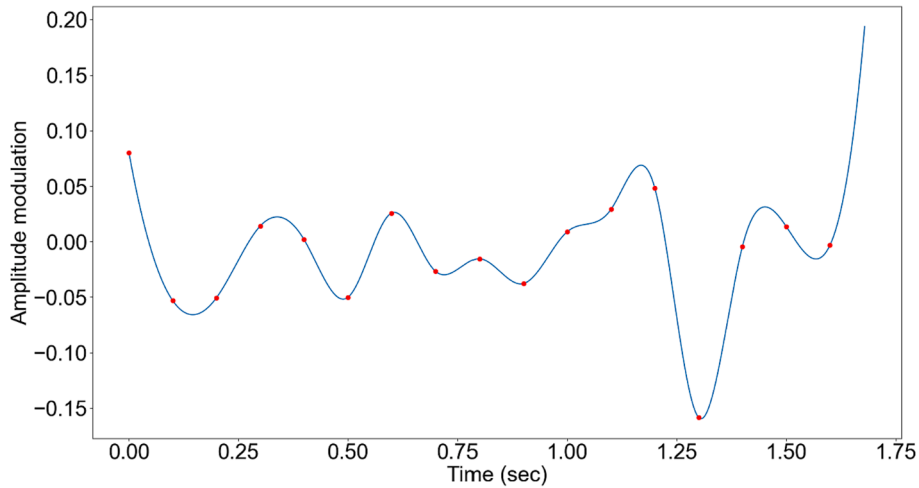


Fig. 7. Example of a random amplitude modulation applied to the noisy part ($0.05 \times \text{Mod}(t)$). The red points represent the 10 equally spaced points with a random value. The blue line represents the cubic spline interpolation alongside the time axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

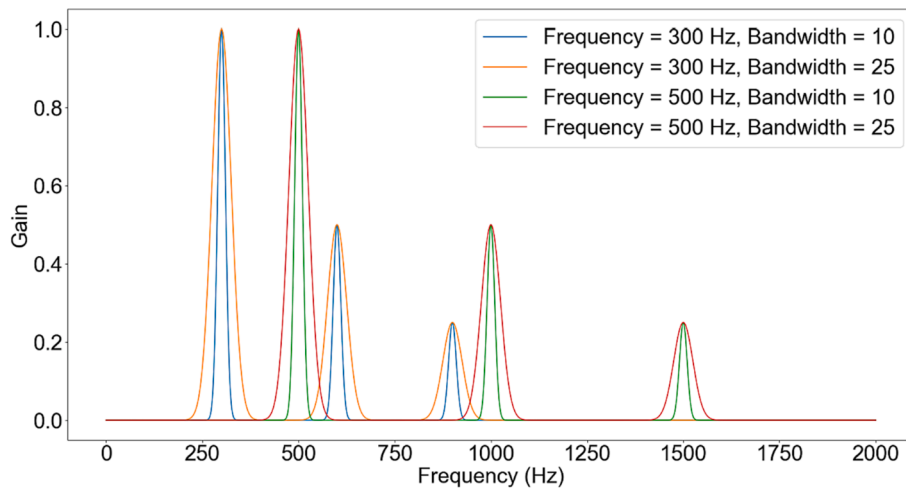


Fig. 8. Gain profile of the different filters used in the tonal part of the stimuli for each combination of fundamental frequency and bandwidth.

the travelling time of the soundwave between the vehicle and the listener for each point in time t as (Eq. (7):

$$effect = \Delta t \times \frac{1}{1 - \frac{V \times x}{c \times r}} \tag{7}$$

where

- Δt represents the time resolution, i.e. the inverse of the sampling frequency of the noise (44100 Hz);
- V is the speed of the vehicle in m/s ($V = 70 \text{ kph} = 19.4 \text{ m/s}$); c , the speed of sound, equal to 340 m/s;
- x is the instantaneous position of the vehicle along its trajectory ($x = V \times t$)
- r is the instantaneous distance between the vehicle and the measurement microphone ($r = \sqrt{d^2 + x^2}$ with $d = 7.5m$).

The amplitude modification represents the increase and decrease in level due to the varying distance between the vehicle and the listener. The source was considered omnidirectional, so that the acoustic pressure varies as the inverse of the distance to the listener (i.e the signal was divided by r at each time value). The modification of a stimulus after applying these two effects can be seen in Fig. 9 (top: time signature; bottom: time–frequency analysis).

Finally, the sounds were filtered to simulate the attenuation of a typical facade. The procedure is the same as in the previous experiment: the same FIR (Finite Impulse Response) filter based on the acoustic isolation of a facade was designed and applied. The final stimuli were then generated by applying a global amplitude factor to get three different sound pressure levels from a single combination of fundamental frequency (F), tonality factor (TF) and bandwidth (Bw). In the previous experiment, maximum sound levels ranged from approximately 27 to 39 dB(A). As some participants related that some levels were low (in spite of the very low background noise level in the booth, which is around 20 dB(A)), it was decided to increase the presentation level of stimuli. As a consequence, the maximum sound pressure levels were selected as 40, 46 and 52 dB(A).

Stimuli have been synthesized using 3 overall sound pressure levels, 2 pitch values, 3 tonality factors, and 2 bandwidths of the tonal components. The values of these parameters are shown in Table 2. However, when tonality factor was set to 0, pitch and bandwidth were meaningless. Therefore, the final dataset was composed of 30 stimuli, each corresponding to a wave file (32 bits, 44100 Hz sampling frequency).

3.1.2. Unpleasantness evaluation of the synthesized noises

Thirty-one students (11 women, 20 men) participated in the listening test. They were between 19 and 27 years old (mean \pm SD age: 22.06 \pm 1.88 years). Their hearing threshold was measured using the same pure tone audiometry procedure as in the first experiment.

The audio equipment and the facility (soundproof booth) were the same as the first experiment. The evaluation of the unpleasantness used a graphical interface developed in-house (already used in many previous studies, for example [23], Fig. 10). Sounds were presented in a random order and the participant answered by moving a slider on a continuous scale. The scale had 5 labels in French ('not at all', 'a little', 'mildly', 'a lot', 'extremely') to guide the participants and allow them to select their answers. Each sound could be played again, as many times as needed by the participant. Participants had to imagine that they were at home, hearing a vehicle passing-by in the street. The operation was repeated for 60 sounds, i.e. two pseudorandom repetitions of the tire noise dataset described above. The duration of the experiment was less than 30 min for each participant.

The experimental protocol (as well as the one used in the following experiment related in that paper) was approved by the Ethics Committee of Lyon University (Comit   d'Ethique de l'Universit   de Lyon) under the number 2022-05-19-001.

Table 2
Summary of the different parameters and their different values.

Frequency	Tonality factor	Bandwidth	Level
300 Hz	0	[F – 8 Hz; F + 8 Hz]	40 dB(A)
500 Hz	0.25	[F – 20 Hz; F + 20 Hz]	46 dB(A)
	0.5		52 dB(A)

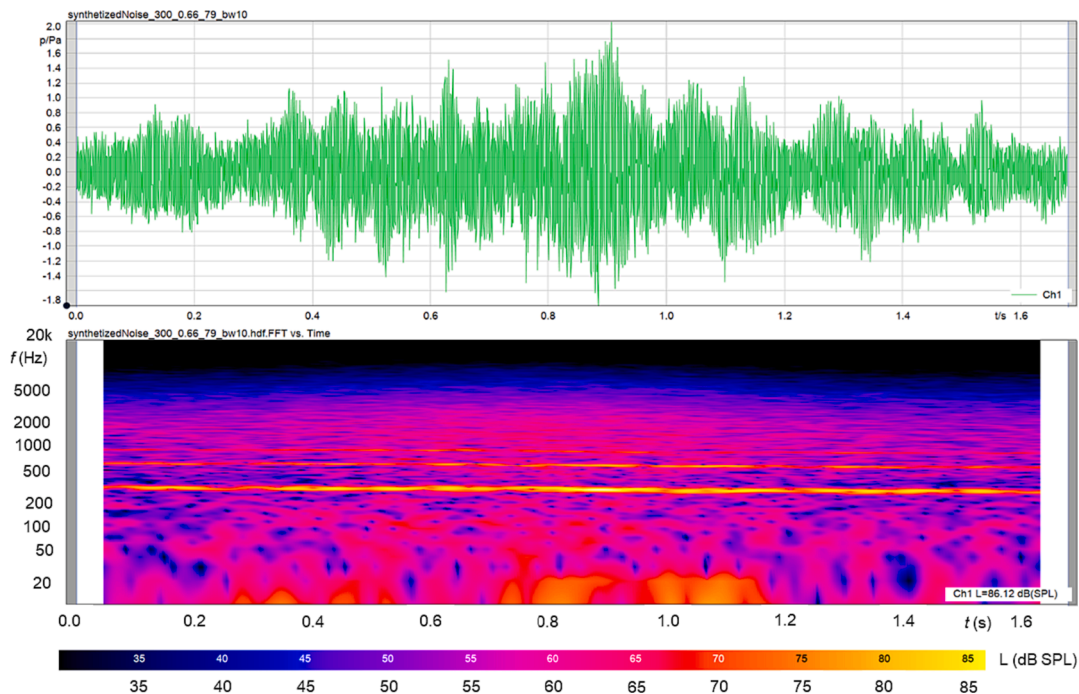


Fig. 9. A synthesized stimulus after the application of the frequency and amplitude shifts. The amplitude rises when the vehicle is approaching and decreases when the truck is getting further away. The frequencies decrease during the entire duration of the sounds.

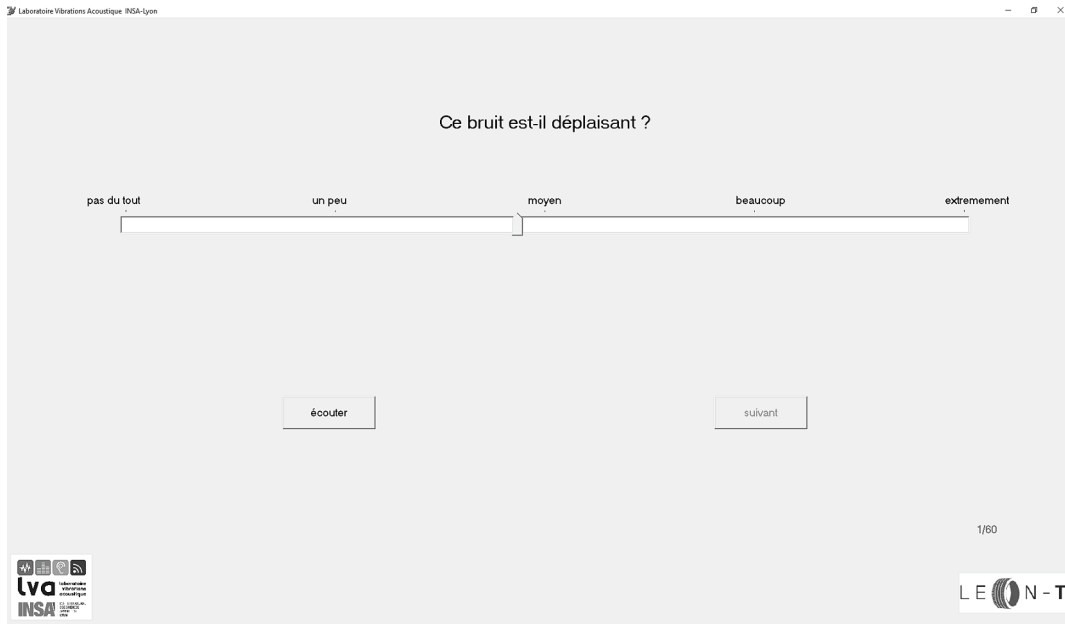


Fig. 10. Interface used by participants to evaluate the unpleasantness of the different stimuli (in French). The question is “Is that noise unpleasant?” and the labels on the scale correspond “not at all”, “a little”, “mildly”, “a lot”, “extremely”. By clicking on the “Ecouter” button, the participant can listen to the sound (as many times as needed). The button “Suivant” allows to validate the answer and move to the next sound.

3.2. Results

3.2.1. Preparation of the data

The position of the slider on the scale was recorded as numbers from 0 (corresponding to “not at all”) and 1000 (“extremely”). The unpleasantness scores for each participant i and each sound j were corrected by mean normalization: the average of all scores given by the participant i was subtracted and the global mean of the data was added (Eq. 12):

$$Centeredscore_{i,j} = score_{i,j} - \frac{1}{n_j} \sum_j score_{i,j} + \frac{1}{n_i \times n_j} \sum_{i,j} score_{i,j} \quad (8)$$

where n_j is the number of stimuli evaluated by a given participant i , ($n_j = 60$) and n_i is the number of participants ($n_i = 31$). First of all, these scores were used to evaluate the consensus between participants. As for the first experiment, a hierarchical clustering of listeners was conducted.

The best mean silhouette criterion was found for two groups but was close to zero (0.10), indicating a random classification of the participants. Thus, it seemed that there was a good consensus in the evaluation of the unpleasantness between participants.

3.2.2. Evaluation of factors effects

The overall results can be seen in Fig. 11. This figure shows the averaged unpleasantness evaluation given by the whole set of participants for each sound (in its 95 % confidence interval). Sounds are labeled as A_B_C_D, where:

- A represents the tonality, set to 0, 0.25 or 0.5;
- B represents the pitch, set to 300 Hz or 500 Hz if some tonal component was present, 0 otherwise;
- C represents the bandwidth of the tone (8, 20 or 0 if no tonal component was present);

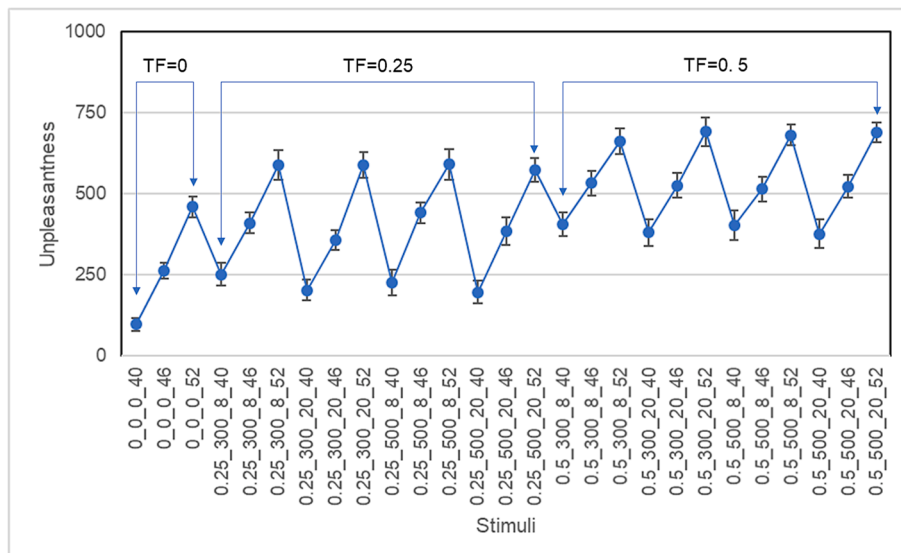


Fig. 11. Averaged unpleasantness evaluations (bars represent the 95% confidence interval of the estimated mean).

- D represents the sound pressure level (40, 46 or 52 dBA).

Three successive stimuli correspond to the same combination of tonality, pitch and bandwidth, the only difference between them being the overall level. The influence of sound pressure level can be clearly seen in Fig. 11, as it could be expected. But the three lines group together sounds sharing the same tonal factor TF. The general trend of the figure represents the effect of this tonal factor on unpleasantness.

In order to evaluate more precisely the influence of factors, two RM-ANOVAs were conducted (using Jasp 0.17.1 [24]). In the first one, the 24 tonal stimuli (i.e. for which tonal factor was 0.25 or 0.5) were used. Within-subject factors were tonal factor (2 levels), pitch (2 levels), bandwidth (2 levels) and level (3 levels). Tonal factor and level were the only significant factors ($p < 0.001$ for both). Significant interactions appeared between participant and tonal factor, pitch and level. In the case of tonal factor and pitch, these interactions consisted in slight differences in the increase of unpleasantness with these two parameters. In the case of pitch, most participants were insensitive to this parameter but, for some of them, the increase of pitch resulted in a small increase (or decrease) of unpleasantness.

Given the very small contribution of pitch and bandwidth, a second RM-Anova was conducted, considering only tonal factor and level as within-subjects factors. In this second analysis, tonal factor had three levels (0, 0.25 and 0.5). This second analysis confirms the nearly equivalent contributions of tonal factor and level on unpleasantness: $F(2, 186) = 488, p < 0.001$ and $\eta_p^2 = 0.84$ for tonal factor, $F(2, 186) = 1079, p < 0.001$ and $\eta_p^2 = 0.92$ for sound level. Fig. 12 shows the influence of these two factors. A small but significant interaction between them can also be detected ($F(4, 372) = 5.4, p < 0.001, \eta_p^2 = 0.055$).

3.2.3. Decision trees

Another way of evaluating the contribution of parameters to unpleasantness was to create a regression tree [25,26]. The explanatory variables were fundamental frequency, tonality factor, bandwidth and overall level. The model was fitted using the R language 4.1.2 and the *rpart* library [17]. The resulting models have the form of binary trees. The partitions are made by consecutive binary splits according to the different explanatory variables, each split dividing the data set in two subsets. The splits are found by minimization of the sum of squared error (SS) according to the mean at the node of the split (SS_T , with mean \bar{y}_T), the left side of the split (SS_L , with mean \bar{y}_L) and the right side (SS_R , with mean \bar{y}_R) of the split (Eq. (9)):

$$\text{minimize}\{SS_T - (SS_L + SS_R)\} = \text{minimize} \tag{9}$$

The complete regression tree is drawn according to this criterion. However, the tree needs to be pruned to avoid the risk of overfitting the model, i.e., the model being too complex (over-parameterized) without having a significant increase in explanatory power compared to a

simpler tree. For each split of the tree, a 10-fold cross-validation is performed: 90 % of the data are randomly selected to fit the model and the 10 other percent are used to validate the model. The process is repeated 10 times. For each repetition, an analog of the PRESS statistic [26] is calculated as the sum of squares of the differences between the observations of the validation dataset (y_i) and their predicted values (\hat{y}_i) (Eq. (10)):

$$PRESS = \sum_i (y_i - \hat{y}_i)^2 \tag{10}$$

Hence, the mean and standard error of the cross-validation error are calculated for each split. A selection rule (1-SE rule) is recommended in [27]: the selected tree is defined as the smallest (simplest) one within one standard error of the best tree (lowest cross-validate relative error).

The full regression tree had 26 splits, following the 1-SE rule, the tree with 7 splits was selected (Fig. 13). The final tree (Fig. 14) shows that, even though they were included in the analysis, the fundamental frequency and the bandwidth of the tones are not considered i.e., they do not have a significant influence on the unpleasantness. As the tree is hierarchical, the closer a node is to the root of the tree, the higher its importance. The maximum global level (52 dB(A)) versus the other levels (40, 46 dB(A)) separates the data in a first step and, thus, seems to be the prominent factor driving the unpleasantness, as shown by the study of the importance. The presence ($TF = 0.25, 0.5$) or absence ($TF = 0$) of a tone then splits the right-hand side of tree (corresponding to a level of 52 dB(A)). For the other levels, the separation is made when the tones are the most present ($TF = 0.5$) against less present or absent ($TF = 0; 0.25$). Further splits are made with the last values of level and tonality factor so that the leaves (end of the tree) correspond to all possible associations of level and TF.

4. Discussion

4.1. Tire noise timbre parameters

Experiment 1 showed that several cues were used by listeners in the free sorting task of exterior sounds (loudness, roughness, spectral balance, tonality). This is in accordance with a previous study [5] and most of these cues can be related to tires characteristics. The sizes of tires included in the panel were quite different: width ranged from 225 mm to 315 mm and the sidewall height ranged from 123 mm to 250 mm. This creates large differences in sound pressure level, hence in loudness (see Fig. 10.11 in [28]). Tonality can be due to the regularity of tread pattern, which can happen on truck tires (while tread pattern is randomised in most car tires). Careful listening to very rough sounds showed that this phenomenon was localised in the frequency range corresponding to tread pattern noise. The contribution of noise emitted by the tread and the sidewall can also influence the frequency balance.

In the case of interior sounds, the consequences of the filtering

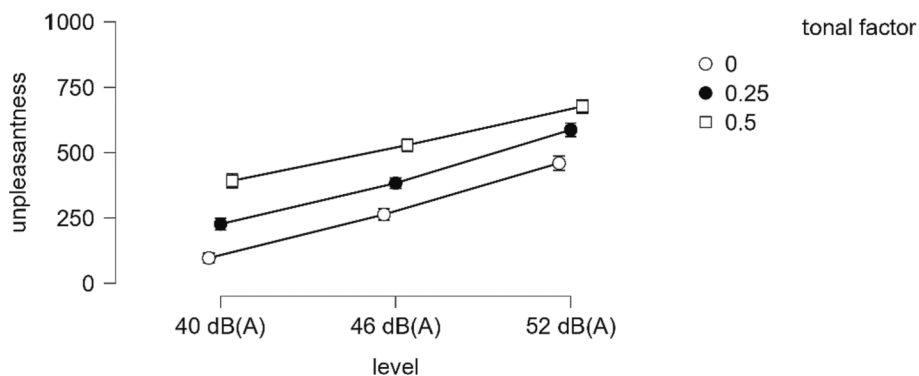


Fig. 12. Effects of tonal factor and sound pressure level on the mean unpleasantness.

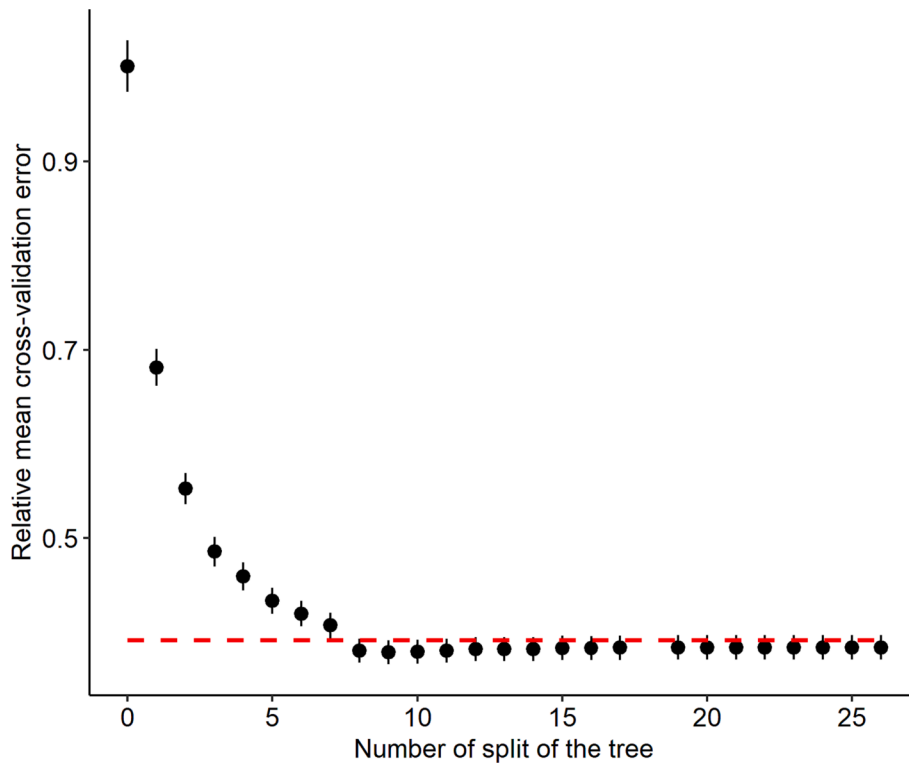


Fig. 13. Selection of the number of splits in the tree according to the 1-SE rule. The relative mean cross-validation is the mean error obtained during the cross-validation process but scaled so that the maximum error equals 1. The dashed red line represents the minimum mean cross-validation error plus its standard error. The mean \pm SE cross-validation error of trees with 7 or more splits are all within this threshold i.e., adding more than 7 splits does not add any further explanatory power to the model. The algorithm did not make a tree with 18 splits but jumped instead to a tree with 19 splits. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

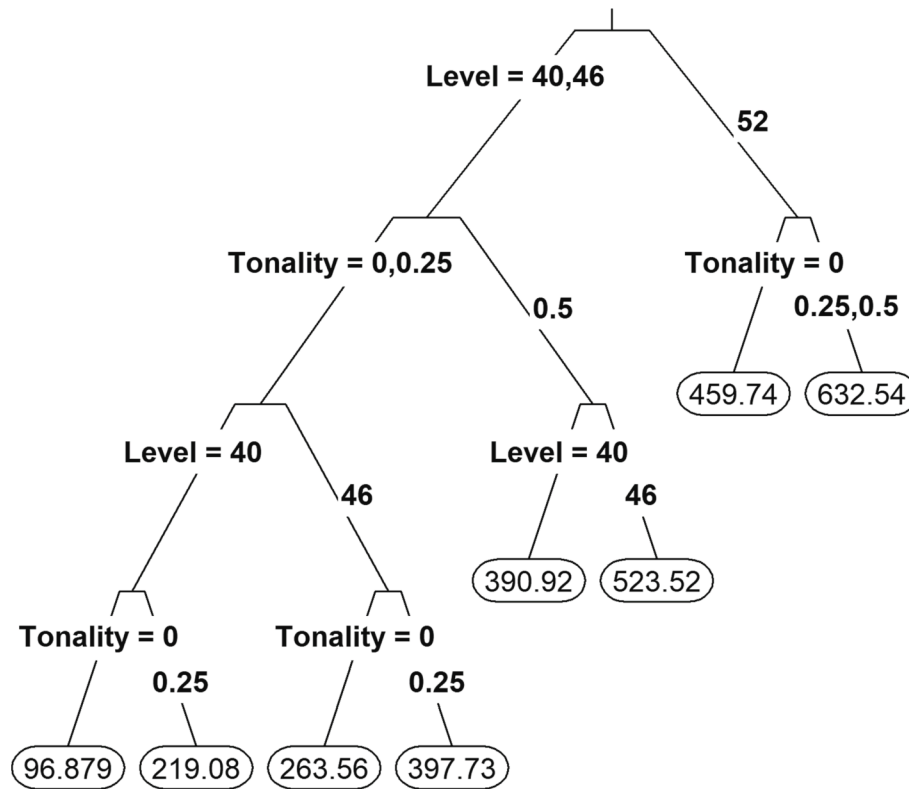


Fig. 14. Final regression tree of the unpleasantness explained by the global level and the tonality factor. The tree starts at the top of the figure and each branch of the tree ends by a leaf containing the mean unpleasantness centered score of the group. The condition of each split is shown on the branches of each node.

applied to sounds are also understandable. Sharpness of all sounds decreased because of the filter shape (see Fig. 1) so that this cue became of second importance to listeners. Filtering also reduced roughness as, in most cases of rough sounds, specific roughness was maximum in the 400 Hz – 1000 Hz frequency range. As Figs. 6 and 7 show, the ratio between maximum and minimum roughness values is not strongly modified by filtering (this ratio is approximately 1.5). But, in the case of indoor sounds, roughness values are strongly reduced so that this cue is no longer noticed by listeners.

The influence of facade filtering is consistent with results of already published studies [29,30]. They show that the modification of various metrics (loudness, sharpness or fluctuation strength) depends on the facade attenuation and the noise characteristics. On the other hand, Neubauer [31] mentioned that tonality was marginally modified (and could even be increased) when applying a facade filtering. All in all, this can explain why loudness and tonality were the key parameters for indoor sound free sorting participants realised in our experiment.

4.2. Unpleasantness of tire noise

Finally, to our knowledge, the highlighting of the importance of tonality in the annoyance of tire noise is new. It is likely that this is due to the fact that the studies already published were focused on the noise of car tires, for which this tonality does not exist. Including noise from heavy vehicles, as did this experiment, has highlighted this phenomenon. In the case of aircraft noise, in which tonality can be prominent, this sound features appeared to be a key factor for annoyance, as well as loudness [32]. ISO 1996-2 [33] or DIN 45681-2002 [34] standards suggest adding a penalty (up to 6 dB) to the A-weighted level of a sound if a tone is audible in that sound. In our experiment, this maximum penalty was reached for tones with the highest tonality (TF = 0.5). However, Fig. 12 shows that this penalty is not large enough to represent the results. Roughly speaking, increasing the tonal factor from 0 to 0.5 increased unpleasantness by around 260 (the scale ranging from 0 to 1000), which represents one labelled category (see Fig. 10). On the other hand, increasing sound level from 40 to 46 dB(A), or from 46 to 52 dB (A), led to a smaller increase of unpleasantness (around 150). Thus, the penalty proposed by the standards underestimates the detrimental contribution of tonality. Of course, the relative contributions of tonality and loudness on unpleasantness determined in our study are certainly dependant on the facade filtering characteristics. We used a simplified facade; but many other types of sound insulation could be used.

5. Conclusion

The aim of this study was to characterise the parameters of the timbre of a tire noise on the perception of this noise. Filtering sounds recorded under standardized conditions (outdoors, 7.5 m from the vehicle's trajectory) showed a reduction in these parameters to loudness and tonality. A second experiment showed that these two parameters have similar contributions to unpleasantness. This study therefore reinforces the fact that tonality should be considered in addition to sound level when evaluating the unpleasantness of tire noise. Taking tonality into account would increase the relevance of tire noise requirements and labelling.

CRediT authorship contribution statement

Thibaut Marin-Cudraz: Investigation, Software, Writing – original draft. **Etienne Parizet:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Beatriz Bragado Perez:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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