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# Impact of urban road traffic on sound unpleasantness: A comparison of traffic scenarios at crossroads

A. Trollé<sup>a\*</sup>, J. Terroir<sup>a</sup>, C. Lavandier<sup>a</sup>, C. Marquis-Favre<sup>b</sup>, M. Lavandier<sup>b</sup>

<sup>a</sup>Laboratoire Mobilités, Réseaux, Territoires et Environnement, Institut Universitaire de Technologie de Cergy-Pontoise - Département Génie Civil, 5 Mail Gay Lussac, Neuville sur Oise, 95031 Cergy-Pontoise Cedex, France

<sup>b</sup>Université de Lyon, Ecole Nationale des Travaux Publics de l'Etat, Laboratoire Génie Civil et Bâtiment, Rue M. Audin, 69518 Vaulx-en-Velin Cedex, France

## Abstract

Sound unpleasantness due to urban road traffic at crossroads was investigated through a listening test performed in a laboratory environment. Thirty-two sound sequences were created. Four factors were studied: sound level, type of crossroads, traffic density and traffic composition. The results showed that sound unpleasantness was mainly influenced by sound level. Decreasing traffic density by a factor of 2 also reduced sound unpleasantness. The roundabout was judged less unpleasant than the crossroads with traffic lights, when traffic density was high. This outcome may be explained by differences in traffic flow dynamics between the crossroads with traffic lights and the roundabout: on the one hand, for the crossroads with traffic lights, the traffic flow resembled a constant pulsed flow, with alternate cycles of acceleration/deceleration; on the other hand, for the roundabout, the traffic flow was more similar to a constant fluid flow, with less marked cycles of acceleration/deceleration. For the roundabout only, sound unpleasantness increased with the presence of heavy vehicles (or buses). Actually, sound sequences with only light vehicles were rated less unpleasant for the roundabout than for the crossroads with traffic lights. This could be due to differences in their spectral pattern. In particular, for traffic-light scenarios, higher levels within the frequency range [400, 3000] Hz occurred when vehicles passed by, in connection with higher vehicle speeds, and higher levels in the high frequencies (around 16 kHz) occurred more often when vehicles stopped, indicating the presence of braking noise with a shrill character.

**Keywords:** Urban road traffic; sound unpleasantness; crossroads; sound level; traffic density; traffic composition.

**PACS:** 43.50.Qp, 43.50.Rq, 43.66.Lj

## 1. Introduction

Mainstream methods for the assessment of the impact of mobility on urban sound climate are mostly based on the measurement and prediction of time-averaged A-weighted sound pressure levels and derived measures (e.g.  $L_{den}$ ). These measures are the basis for the calculation of the noise maps required by the European Directive 2002/49/EC [1]. This calculation has been extended to mapping the expected percentage of highly annoyed people, using exposure-response relationships [2]. Whatever the type of map, traffic is commonly modeled as a steady sound source flow. Yet, recent research has shown that traffic flow dynamics has an influence on urban soundscapes [3] and that accounting for it allows noise assessment to be improved [4]. As suggested by Can et al. [4], "the impact of traffic flow dynamics on human noise perception should finally be investigated,

\*Corresponding author. Tel.: +33951858216.

Email addresses: arnaud.trolle@yahoo.fr (A. Trollé), jonathan.terroir@u-cergy.fr (J. Terroir), catherine.lavandier@u-cergy.fr (C. Lavandier), Catherine.MARQUISFAVRE@entpe.fr (C. Marquis-Favre), Mathieu.LAVANDIER@entpe.fr (M. Lavandier)

to propose a global tool that greatly improves noise impact assessment of urban traffic management policies”. But, until now, the impact of traffic flow dynamics on human beings, measured in terms of noise annoyance or sound unpleasantness, has been sparsely studied. In particular, urban traffic management policies at crossroads and their impact on urban soundscapes need to be further investigated. Hence, one aim of this study was to enhance the understanding of the potential effects of traffic characteristics on sound unpleasantness due to road vehicle pass-byes, for various scenarios at crossroads.

In the field of community noise annoyance, studies have shown that an increase in the sound level emitted by vehicles and an increase in their number lead to an increased annoyance, in particular when these vehicles are heavy vehicles [5]. Moreover, regarding traffic at crossroads, other studies based on road traffic modeling [6, 7] or field measurements of road traffic [8] have shown that a roundabout leads to lower sound levels compared to a crossroads with traffic lights. Beyond assessing physical sound levels due to road traffic at crossroads, a recent study [9] investigated the perceptual aspects of road traffic noise, by studying annoyance due to a variety of traffic noise scenarios, differing in terms of traffic density, traffic composition and driving condition (i.e. type of crossroads). The authors performed a Principal Component Analysis on their annoyance data. By forming “semantic clusters” of traffic scenarios, their results showed that i) a crossroads with traffic lights was more annoying than a roundabout, ii) traffic scenarios with a low density were the least annoying, and iii) traffic scenarios involving heavy vehicles led to higher annoyance.

The present study further investigated the perceptual aspects of road traffic noise at crossroads. It aimed to evaluate simultaneously the effects of the factors mentioned above (i.e. sound level emitted by vehicles, type of crossroads, traffic density or number of vehicles, and traffic composition) on sound unpleasantness. In contrast with the study [9] mentioned above, the data analysis performed here made it possible to assess potential interactions between the four factors studied. A listening test in a laboratory environment was carried out. Sound sequences were created from stereophonic sound recordings performed in Tonkin neighborhood, in Villeurbanne, France. Sound sources were light vehicles, heavy vehicles and buses, in agreement with traffic data given by local authorities. The differences in speed and rhythm (accelerations or decelerations more or less sudden) were studied *via* two types of crossroads, crossroads with traffic lights or roundabout. Traffic density was studied by simulating off-peak and peak traffics in this neighborhood.

## 2. Methods

### 2.1. Stimulus preparation

Five urban sites located in Tonkin neighborhood were selected for *in situ* sound recordings: i) sites A and B (crossroads with traffic lights): two bus lines cross these sites, open to heavy vehicles; ii) site C (roundabout): two bus lines cross this site, open to heavy vehicles; iii) sites D and E (roundabouts): no bus line crosses these sites, open to heavy vehicles. The recordings were performed using an ORTF couple Schoeps MSTC 64 (in accordance with the stereophonic sound reproduction system selected, see Section 2.2) equipped with Schoeps BBG windscreens, along with an omnidirectional microphone (used for the system calibration). This recording procedure was similar to

the one adopted in [22] for instance. Moreover, the ORTF couple was previously used in other sound perception research in order to record noises emitted by moving sources such as road vehicles (e.g. [10]). The ORTF couple was placed in accordance with standard NF S 31-010[11]; the omnidirectional microphone was placed in the center of the ORTF couple, slightly above. The distance between the microphones and the nearest traffic line was imposed by the urban architecture as well as by the specifications of the standard mentioned above; it varied between 4 and 5 meters.

Sound samples corresponding to distinct vehicle pass-by noises were extracted from the sound sequences recorded off-peak. Attention was paid to selecting sound samples without any unwanted sound (wind, voices, birds, etc.).

In this study, four factors were investigated:

- Sound level, testing two levels. The first sound level was set to the recording level of the sound samples minus 3.5 dB(A), so that the sound reproduction levels could be comfortable for listening in the laboratory conditions. The second sound level was set to their recording level minus 7.5 dB(A). This difference of 4 dB(A) was chosen so that it could be noticeable when listening. Moreover, these two levels seemed practical, i.e. they could refer to two practical distances from the passer-by to the crossroads.
- Type of crossroads, testing two levels: crossroads with traffic lights (CR) and roundabout (RA).
- Traffic density, testing two levels: low (off-peak period) and high (peak period). The first level was a traffic density of 400 vehicles (including all kinds of vehicles) per hour for both traffic directions, the second level was a traffic density of 800 vehicles per hour. These traffic densities were in agreement with traffic count data given by local authorities.
- Traffic composition, testing four levels: i) 100% light vehicles (LV), 0% heavy vehicles (HV), 0% bus; ii) 80% LV, 10% HV, 10% bus; iii) 80% LV, 5% HV, 15% bus; iv) 90% LV, 0% HV, 10% bus. These traffic compositions were plausible, with respect to traffic count data given by local authorities.

For each possible combination of these factor levels, a sound sequence of 3 minutes was created. Altogether 32 sound sequences were created (see Table 1). For the crossroads with traffic lights, a duration of 3 minutes allowed for two complete cycles of lights to be taken into account (one cycle consisted of 45 seconds for green lights and 25 seconds for red lights). Moreover, it allowed for the duration of the listening test and the listener's fatigue to be reduced. For each type of crossroads and each traffic density, a sequence of light vehicle pass-byes in both traffic directions (32 LV for a high traffic density, 16 LV for a low traffic density) was created as a common basis for all corresponding sequences<sup>1</sup>. Then, depending on traffic composition, the remaining vehicles (LV and/or HV and/or buses) were added to these sequences of LV, until the maximal number of vehicles was reached (40 for a high traffic density, 20 for a low traffic density). HV and buses were

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<sup>1</sup>The light vehicle pass-byes inserted within each basic sequence were different from each other, for the sake of realism.

evenly spaced out in the sound sequences<sup>2</sup>. The sound sequences were created using the software Sony Soundforge<sup>®</sup>. To add a vehicle pass-by to a sound sequence, its “mix” tool was used, with a fade-in/fade-out performed on the pass-by noise comprised between 0.5 and 1 second.

Table 1: The 32 sound sequences created. CR: crossroads with traffic lights; RA: roundabout; LV: light vehicle; HV: heavy vehicle;  $L_{A,eq}$ : A-weighted equivalent sound level.

N°	Sound level	Crossroads	Traffic density	Traffic composition		$L_{A,eq}$ [dB(A)]
				%	Number of vehicles	
1	1	CR	Low	100%LV, 0%HV, 0%Bus	20 LV, 0 HV, 0 Bus	56.8
2	1	CR	Low	80%LV, 10%HV, 10%Bus	16 LV, 2 HV, 2 Buses	58.3
3	1	CR	Low	80%LV, 5%HV, 15%Bus	16 LV, 1 HV, 3 Buses	58.0
4	1	CR	Low	90%LV, 0%HV, 10%Bus	18 LV, 0 HV, 2 Buses	57.7
5	1	CR	High	100%LV, 0%HV, 0%Bus	40 LV, 0 HV, 0 Bus	61.1
6	1	CR	High	80%LV, 10%HV, 10%Bus	32 LV, 4 HV, 4 Buses	61.8
7	1	CR	High	80%LV, 5%HV, 15%Bus	32 LV, 2 HV, 6 Buses	61.5
8	1	CR	High	90%LV, 0%HV, 10%Bus	36 LV, 0 HV, 4 Buses	61.6
9	1	RA	Low	100%LV, 0%HV, 0%Bus	20 LV, 0 HV, 0 Bus	52.8
10	1	RA	Low	80%LV, 10%HV, 10%Bus	16 LV, 2 HV, 2 Buses	57.6
11	1	RA	Low	80%LV, 5%HV, 15%Bus	16 LV, 1 HV, 3 Buses	57.5
12	1	RA	Low	90%LV, 0%HV, 10%Bus	18 LV, 0 HV, 2 Buses	55.7
13	1	RA	High	100%LV, 0%HV, 0%Bus	40 LV, 0 HV, 0 Bus	56.0
14	1	RA	High	80%LV, 10%HV, 10%Bus	32 LV, 4 HV, 4 Buses	59.9
15	1	RA	High	80%LV, 5%HV, 15%Bus	32 LV, 2 HV, 6 Buses	60.0
16	1	RA	High	90%LV, 0%HV, 10%Bus	36 LV, 0 HV, 4 Buses	58.2
17	2	CR	Low	100%LV, 0%HV, 0%Bus	20 LV, 0 HV, 0 Bus	52.9
18	2	CR	Low	80%LV, 10%HV, 10%Bus	16 LV, 2 HV, 2 Buses	54.3
19	2	CR	Low	80%LV, 5%HV, 15%Bus	16 LV, 1 HV, 3 Buses	54.1
20	2	CR	Low	90%LV, 0%HV, 10%Bus	18 LV, 0 HV, 2 Buses	53.7
21	2	CR	High	100%LV, 0%HV, 0%Bus	40 LV, 0 HV, 0 Bus	57.1
22	2	CR	High	80%LV, 10%HV, 10%Bus	32 LV, 4 HV, 4 Buses	57.8
23	2	CR	High	80%LV, 5%HV, 15%Bus	32 LV, 2 HV, 6 Buses	57.5
24	2	CR	High	90%LV, 0%HV, 10%Bus	36 LV, 0 HV, 4 Buses	57.6
25	2	RA	Low	100%LV, 0%HV, 0%Bus	20 LV, 0 HV, 0 Bus	48.9
26	2	RA	Low	80%LV, 10%HV, 10%Bus	16 LV, 2 HV, 2 Buses	53.6
27	2	RA	Low	80%LV, 5%HV, 15%Bus	16 LV, 1 HV, 3 Buses	53.6
28	2	RA	Low	90%LV, 0%HV, 10%Bus	18 LV, 0 HV, 2 Buses	51.8
29	2	RA	High	100%LV, 0%HV, 0%Bus	40 LV, 0 HV, 0 Bus	52.0
30	2	RA	High	80%LV, 10%HV, 10%Bus	32 LV, 4 HV, 4 Buses	56.0
31	2	RA	High	80%LV, 5%HV, 15%Bus	32 LV, 2 HV, 6 Buses	56.1
32	2	RA	High	90%LV, 0%HV, 10%Bus	36 LV, 0 HV, 4 Buses	54.3

For the sound sequences at the first sound level (level “1” in Table 1), the vehicle sequences were mixed at their recording level with a background noise (recorded *in situ*) at its recording level ( $L_{A,eq} = 38.4$  dB(A)). Then, the sound level was reduced by 3.5 dB(A). For the sound sequences at the second sound level (level “2” in Table 1), the sound level of the original vehicle sequences (without any background noise) was reduced by 7.5 dB(A) (with respect to their recording level). The sound level of the background noise was only reduced by 3.5 dB(A) (with respect to its recording level). Then, the vehicle sequences obtained were mixed with the resulting background noise. The sound level of the background noise was thus the same for both series of sequences ( $L_{A,eq} = 34.9$  dB(A)). Hence, levels “1” and “2” implied two levels of emergence of the vehicle pass-by noises from the background noise, differing by 4 dB(A).

## 2.2. Laboratory environment and listeners

The listening test took place in a quiet room (background noise level: 22 dB(A)) whose setting was simulating the terrace of a café, in order to be as close as possible to the imaginary situation proposed (see hereafter). The listener was seated in a comfortable chair in front of a round table, on which a laptop was placed. The sound sequences were reproduced using a 2.0 system composed of two loudspeakers (GENELEC 1031A)

<sup>2</sup>For instance, for sequence N°2 (16 LV, 2 HV, 2 Buses), HV and buses were spaced out approx. every 35 seconds.

and a high quality sound card (M-Audio QUATTRO). The stereophonic sound reproduction is known for its good representation, readability, plausibility and overall quality of reproduction when studying fixed or moving acoustical sources [13].

Thirty-five listeners participated in the test. All declared having normal hearing abilities. They were paid for their participation.

### 2.3. Experimental procedure

The experimental procedure was similar to the one adopted in previous studies (e.g. [14]). Before the beginning of the test, the following instructions were displayed on the laptop screen: “In this test, you will hear excerpts of urban sound environment while you will have reading activities. For each excerpt, we ask you to evaluate unpleasantness. To evaluate this, imagine yourself reading at the terrace of a café. You have to rate unpleasantness on a continuous scale ranging from 0 to 10. Rate 0 if you consider the sound environment to be not at all unpleasant and rate 10 if you consider the sound environment to be extremely unpleasant. If you are between these two situations, choose an intermediate rating between 0 and 10. You will hear each excerpt once. After answering and validating your answer, you will not be able to go back. Take your time to answer”.

Then, the stimuli were presented one by one in random order. For each stimulus, the participants were asked to evaluate sound unpleasantness. For each excerpt, a message was appearing on the screen, reminding the imaginary situation and asking for a judgment: “Imagine yourself reading at the terrace of a café. While reading, you are in this urban sound environment. How would you judge this urban sound environment?”. The answer scale was inspired by the recommendations of standard ISO/TS 15666 [15]. To answer, the participants had to move a cursor along a continuous scale ranging from 0 to 10 with 11 numerical labels evenly spaced out. Two verbal items (“not at all unpleasant” and “extremely unpleasant”) were associated with the scale ends, 0 and 10 respectively.

At the end of the test, the participants were asked to freely describe the sound excerpts they heard and to indicate their criteria of evaluation.

## 3. Results

### 3.1. Inspection of inter-individual differences

Fig. 1 shows the mean unpleasantness scores and standard deviations across the listeners, for the 32 sound sequences. One can observe that the mean unpleasantness scores vary within a limited range of the 0-10 scale, i.e [2.90, 6.14]. Hence, the potential effects of the 4 factors (and of their interactions) on sound unpleasantness (see Section 3.2) are unlikely to be large.

Also, one can note that the standard deviations are comprised between 1.42 and 2.09 units (on the 0-10 scale). These values are somewhat comparable to those observed by Guidati *et al.* [9], around 1 (but on a 1-9 scale). The inter-individual differences in ratings are substantial here for the 32 sound sequences. These inter-individual differences could have been due to different answering strategies, but also to differences in the way sound sequences were perceived [16]. A cluster analysis was thus carried out using Hierarchical Ascending Classification [17] in order to determine whether there were subgroups of listeners or outliers that could explain these large inter-individual differences. The results of this cluster analysis (not detailed here for the sake of brevity) did not reveal any presence of subgroups or outliers.

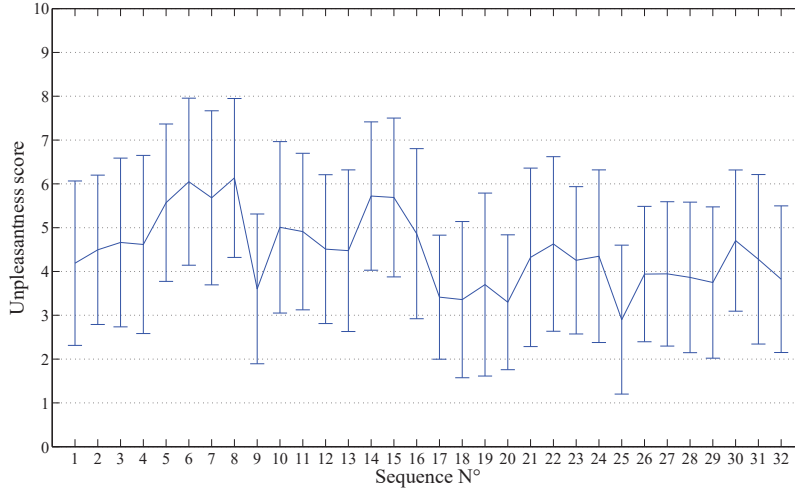


Figure 1: Mean unpleasantness scores and standard deviations across the listeners, for the 32 sound sequences. —: mean value; |: standard deviation.

### 3.2. Effects of the 4 factors (and of their interactions) on sound unpleasantness

A repeated measures analysis of variance (RM ANOVA) was performed in order to assess the effects of the different factors and of their interactions on sound unpleasantness. This RM ANOVA implied four within-subject factors: “sound level”, “type of crossroads”, “traffic density” and “traffic composition”. In the following, only the significant results of hypothesis testing in the RM ANOVA are presented.

The results of hypothesis testing for sound level and traffic density were highly significant ( $F(1,34)=112.5$ ,  $p<0.001$  and  $F(1,34)=101.7$ ,  $p<0.001$ , respectively). According to the  $\omega^2$  effect size measure [18], the corresponding main effects remained, however, medium ( $\omega^2 = 7.5\%$  for sound level) or small ( $\omega^2 = 4.6\%$  for traffic density), confirming that unexplained variance due to inter-individual differences was important.

The result of hypothesis testing for the type of crossroads was significant ( $F(1,34)=5.7$ ,  $p<0.05$ ). But this main effect was tiny ( $\omega^2 = 0.2\%$ ). In fact, the type of crossroads had an influence on sound unpleasantness in interaction with traffic density or traffic composition. Indeed, the results of hypothesis testing for these two interactions (i.e. the one between the type of crossroads and traffic density and the other between the type of crossroads and traffic composition) were highly significant ( $F(1,34)=20.8$ ,  $p<0.001$  and  $F(3,102)=7.9$ ,  $p<0.001$ , respectively). Their effect remained small ( $\omega^2 = 0.5\%$  and  $\omega^2 = 0.7\%$ , respectively). Tukey’s HSD test revealed that the roundabout was less unpleasant than the crossroads with traffic lights for the high traffic density. This was not the case for the low traffic density (see Fig. 2). For the roundabout, a traffic consisting of only light vehicles was less unpleasant than a mixed traffic (i.e. with heavy vehicles and/or buses), but this effect did not exist for the crossroads with traffic lights (see Fig. 3). Owing to the presence of the (small) interaction effect between the type of crossroads and traffic composition, it would be dubious to interpret the main effect of traffic

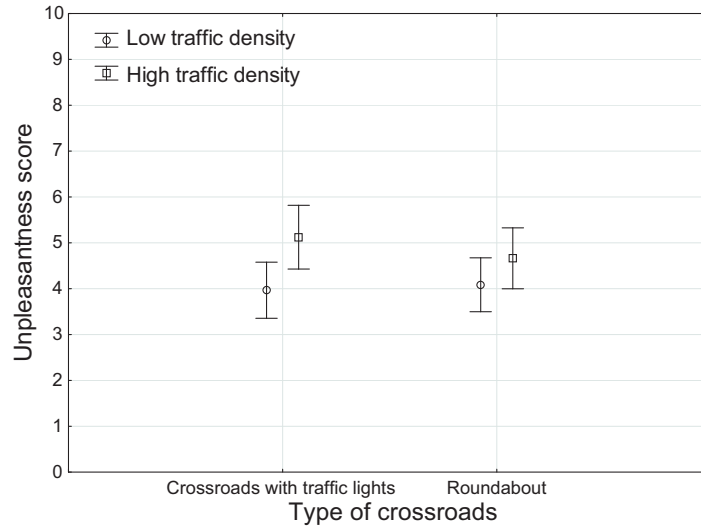


Figure 2: Mean unpleasantness scores and standard errors across the listeners, the sound levels and the traffic compositions, for the 4 levels of the interaction between the type of crossroads and traffic density. o, □: mean value; |: standard error.

composition [19]. Concerning this main effect, the result of hypothesis testing was also highly significant ( $F(3,102)=13.0$ ,  $p<0.001$ ) and the effect size was small ( $\omega^2 = 1.7\%$ ).

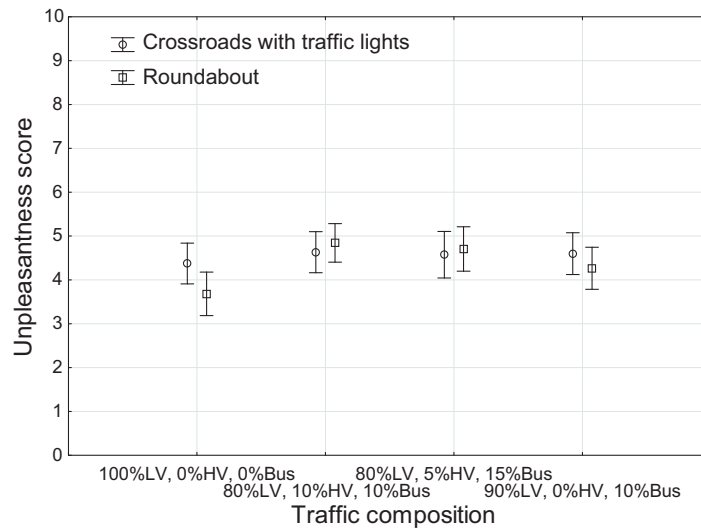


Figure 3: Mean unpleasantness scores and standard errors across the listeners, the sound levels and the traffic densities, for the 8 levels of the interaction between the type of crossroads and traffic composition. o, □: mean value; |: standard error; LV: light vehicle; HV: heavy vehicle.

Finally, the result of hypothesis testing for the interaction between sound level and



traffic density was significant ( $F(1,34)=5.1$ ,  $p<0.05$ ); but this interaction effect was tiny ( $\omega^2 = 0.1\%$ ).

### 3.3. Analysis of the free verbalizations

The descriptive criteria used by the 35 participants to justify their unpleasantness scores were, in order of importance: i) the perceived loudness or distance (43 occurrences of substantives + 22 occurrences of adjectives); ii) the type of vehicle, heavy vehicles being more unpleasant (19 + 0 occurrences); iii) the traffic dynamics, pass-byes or stops/starts for example (14 + 3 occurrences); iv) the traffic density or number of vehicles (10 + 4 occurrences); v) the duration of the sound events (4 + 1 occurrences); and vi) the spectral sensations (1 + 4 occurrences).

These results show that, in addition to sound level, other factors, such as the type of vehicle, the traffic dynamics, the number of vehicles and the spectral content, also influenced the participants' unpleasantness judgments.

## 4. Discussion

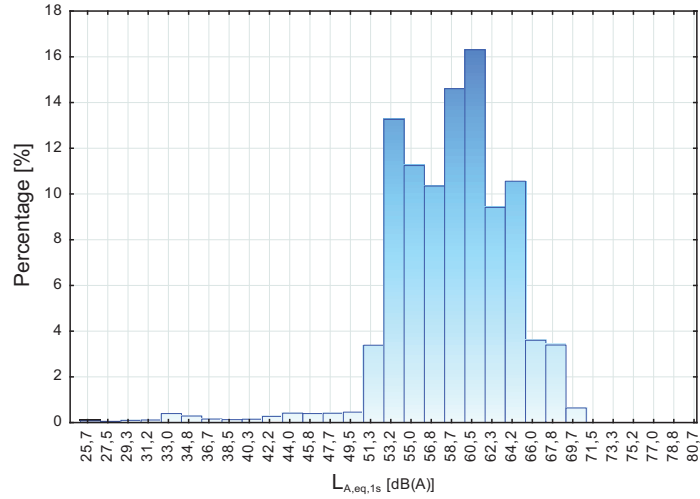
In their field study, Decký *et al.* [8] showed that a reconstruction of a crossroads with traffic lights into a roundabout could lead to a reduction in sound level of 2.2 to 6 dB, for a mixed traffic (i.e. with light and heavy vehicles). Using simulations, Chevallier *et al.* [7] showed that replacing a traffic light by a roundabout could induce a reduction in sound level of up to 2.5 dB(A), for low and medium traffics of light vehicles (400 and 700 vehicles per hour, respectively). Here, reductions in sound level of the same order could be noted. For the low traffic density, the average reduction when passing from a crossroads with traffic lights to a roundabout was 1.5 dB(A) and, for the high traffic density, the average reduction was 2.7 dB(A). These congruent results partially validate the methodology used here to simulate traffic scenarios for the crossroads with traffic lights and the roundabout.

Not surprisingly, sound unpleasantness was found to be highly linked to sound level in this study. The RM ANOVA results showed that this factor, among all the different factorial sources of variation, implied the largest measured effect size. The results of the free verbalization task (i.e. 65 verbalizations for the perceived loudness or distance) also showed its prominent influence on sound unpleasantness. The difference between the two levels of emergence, i.e. 4 dB(A), seemed clearly responsible for this prominent effect on sound unpleasantness. The two sound levels seemed to make sense to the participants if one refers to their verbalizations associated to perceived distance.

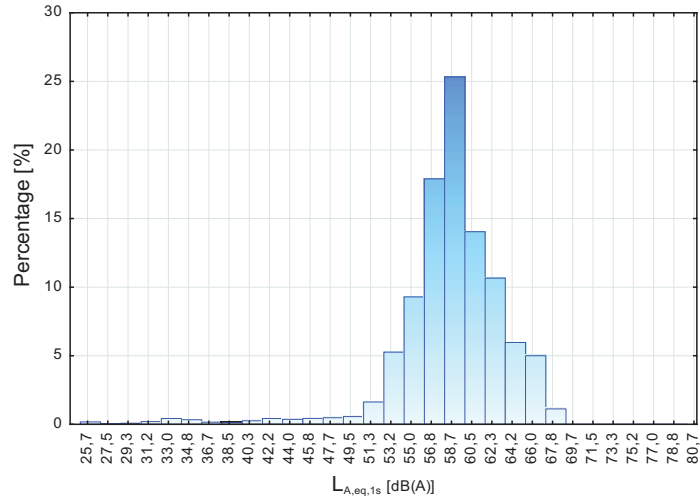
In their study, Guidati *et al.* [9] showed, by performing a Principal Component Analysis on their annoyance data, that traffic scenarios with a low traffic density were the least annoying. Similarly, in the present study, the RM ANOVA results showed that reducing traffic density by a factor of 2 led to lower sound unpleasantness. This outcome was also supported by the results of the free verbalization task (14 verbalizations for the number of vehicles).

Also, Guidati *et al.* [9] showed that traffic light scenarios were more annoying than roundabout situations. In the present study, a similar outcome could be noted, but additional information could be gathered: the roundabout was less unpleasant than the crossroads with traffic lights, only when the traffic density was high. This outcome may

be explained by differences in traffic flow dynamics between the crossroads with traffic lights and the roundabout, when the traffic density is high. Fig. 4 shows histograms of the  $L_{A,eq,1s}$  values for two sound sequences that both involved the high traffic density (with the same traffic composition: 80%LV, 5%HV, 15%Bus), but differed in the type of crossroads: sequence N°7 (CR) and sequence N°15 (RA). For sequence N°7, the



a)



b)

Figure 4: Histograms of the  $L_{A,eq,1s}$  values for two sound sequences that both involved the high traffic density, but differed in the type of crossroads. (a) Sequence N°7 (CR); (b) Sequence N°15 (RA).

distribution of the  $L_{A,eq,1s}$  values follows closely that typically observed for a constant pulsed flow [20]. This type of flow implies alternate cycles of acceleration/deceleration [20], which may have been judged here more unpleasant by the participants. For sequence

N°15, the distribution of the  $L_{A,eq,1s}$  values rather matches that typically observed for a constant fluid flow [20]. This type of flow involves a continuous movement of vehicles on a roadway, with random vehicle arrival times and speeds [20]. In the present case, cycles of stops/starts remained (because of the possible presence of traffic within the roundabout), though they were less marked. This more continuous flow may have been judged less unpleasant by the participants. The effect of flow dynamics on sound unpleasantness could also be seen through the results of the free verbalization task (16 verbalizations for the flow dynamics, among which “starts” and “stops” were associated with higher sound unpleasantness by 4 participants).

Moreover, Guidati *et al.* [9] pointed out that the presence of heavy vehicles in the traffic flow led to higher annoyance. Once again, in the present study, a similar outcome could be noted, but supplementary information could be gathered: the presence of heavy vehicles and/or buses led to higher mean unpleasantness scores, but only for the roundabout. Actually, one can note in Fig. 3 that the sound sequences with only light vehicles were rated less unpleasant for the roundabout than for the crossroads with traffic lights. This could be due to differences in their spectral pattern. To illustrate this point, Fig. 5 shows auditory spectrograms [12] of sound sequences N°5 and N°13, which both involved only light vehicles (with the high traffic density), but differed in the type of crossroads (CR for sequence N°5 and RA for sequence N°13). For sequence N°5 (CR), one can observe that, with respect to sequence N°13 (RA): i) higher levels within the frequency range [400, 3000] Hz (circled in dashed line in Fig. 5(a)) occurred when the traffic light was green, i.e. when vehicles passed by; ii) higher levels in the high frequencies, around 16 kHz (circled in solid line in Fig. 5(a)), occurred when the traffic light turned to red, i.e. when vehicles stopped. The higher levels within the frequency range [400, 3000] Hz may have been judged unpleasant by participants. These levels are likely to be linked to higher vehicle speeds [21] for the crossroads with traffic lights than for the roundabout, for which vehicles have to slow down when approaching. The higher levels around 16 kHz indicate the presence of braking noise with a shrill character [22], which may have been judged negatively by participants. This type of frequency content is likely to be more frequent for the crossroads with traffic lights. The results of the free verbalization task (5 verbalizations for the spectral features) also plead for an impact of the spectral features on sound unpleasantness.

Finally, the interaction between sound level and traffic density is not discussed here since it was shown in Section 3.2 that its effect was too tiny.

With an operational point of view, by taking account of the perceptual aspects, it seems that the positive effect of a roundabout would be larger for a high traffic density without any heavy vehicle (and/or bus).

## 5. Conclusions

From the unpleasantness scores and the verbalization data given by the participants during the test, the following conclusions can be drawn:

- i) Sound unpleasantness was – not surprisingly – highly linked to sound level.
- ii) Sound unpleasantness was also linked to traffic density (the more vehicles, the more unpleasant).

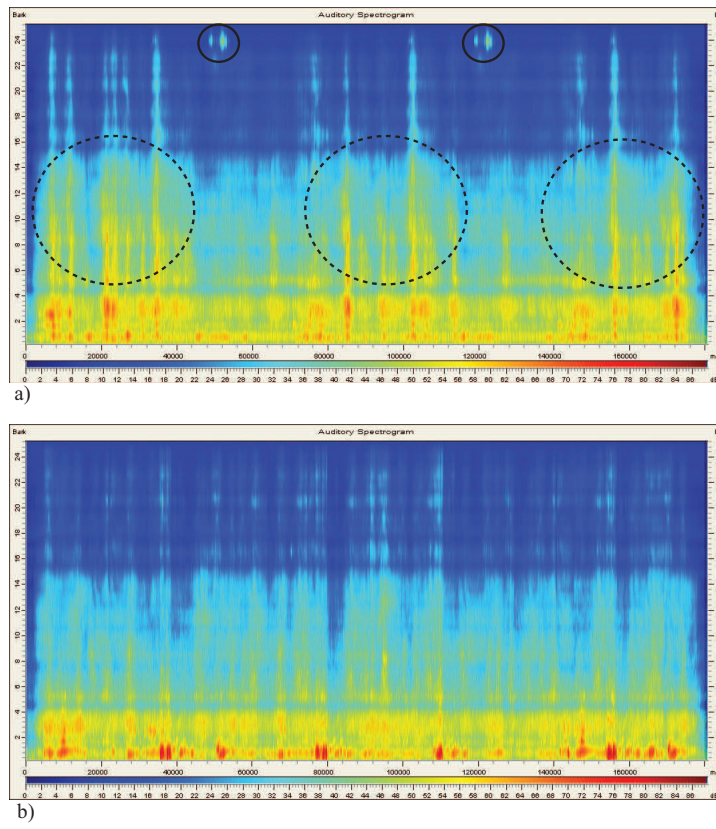


Figure 5: Auditory spectrograms. (a) Sequence N°5 (CR); (b) Sequence N°13 (RA).

- iii) Sound unpleasantness was also linked to the type of crossroads, but only in interaction with traffic density or traffic composition: a roundabout was less unpleasant than a crossroads with traffic lights, for a high traffic density; for a roundabout, a traffic consisting of only light vehicles was less unpleasant than a mixed traffic (i.e. with heavy vehicles and/or buses), confirming that the presence of heavy vehicles or buses in the traffic could lead to an increased sound unpleasantness.

It is important to note that the results obtained are specific to a French neighborhood. The sound sequences were not equalized in loudness and the diversity of the vehicles, excluding powered-two-wheelers, was limited to real situations in Villeurbanne. Results could have been different if sound sequences had simulated more extreme situations in larger cities. Further works could investigate other vehicles, such as powered-two-wheelers. Loudness equalization could also be considered in order to investigate deeply how the temporal and spectral features of sound sequences influence sound unpleasantness.

Finally, one limitation of the present study lies in the fact that only one modality, i.e. audition, was investigated in relation to the perception of road traffic noise at crossroads. Previous works (e.g. [23, 24]) showed that the perception of the environment noise was bimodal, in particular that complex interactions between audition and vision could have an influence on the perception of urban soundscapes. Hence, further work should investigate how various aspects of the visual stimuli could affect sound unpleasantness due to urban road traffic at crossroads.

## Policy and ethics

All procedures reported on this note were undertaken, since they involved humans, in compliance with The Code of Ethics of the World Medical Association (Declaration of Helsinki), University of Cergy-Pontoise also approving their performance. Likewise, all tests were carried out with all listeners' consent, the privacy rights of human participants being always assured.

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