Physical and perceptual characterization of road traffic noises in urban areas for a better noise annoyance assessment

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ACOUSTICS 2012

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The work presented in this paper intends to contribute to improve noise maps by a more meaningful characterization of urban road traffic noises. In this aim, *in situ* recorded pass-by noises, following an *a priori* physical typology, are submitted to a panel of subjects *via* a free categorization and free verbalization tasks. This resulted in the proposal of a perceptual and cognitive typology of road traffic pass-by noises that was further confirmed by the results of a pair-wise comparison test. The 7 categories of the perceptual and cognitive typology were then studied separately from noise annoyance point of view. Annoyance indicators were then proposed to characterize each category of vehicle pass-by noises by taking into account their spectral and temporal specificities.

1 Towards an improvement of noise maps

Community noise, and especially road traffic noise, is still a major environmental concern for most people in urban areas (e.g. [1]). Moreover according to WHO, contrary to other environmental pollutions, the exposure to environmental noise seems to increase in European countries [2].

In 2002, the European Commission gave a regulatory answer to this environmental concern, with the European Directive 2002/49/EC [3]. The main goal is the information and communication to the public about environmental noise, and one of the measures is to build noise maps for various community noises for every European city of more than 100,000 inhabitants [3].

Noise maps present the noise exposure situation by using the energy-based index L_{den} (the day-evening-night level) [3]. Connected to dose-response relationships [4, 5], these noise maps could then be interpreted as annoyance maps.

However, *in situ* studies on noise annoyance generally reveal that energy-based indices are only able to explain about one-third of annoyance responses given by individuals [6, 7]. In addition, it is recognized that energy-based indices are not able to take into account spectral and temporal specificities of noise sources, that have an influence on judgments of either long-term annoyance studied *in situ* (e.g. [7, 8]), or short-term annoyance studied in laboratory conditions (e.g. [9, 10]).

Focusing on road traffic in urban areas, the main goal of our work is to contribute to an improvement of noise maps, by the definition of more meaningful annoyance indicators that are able to account for other relevant specificities (spectral and temporal) of road traffic noise, in addition to loudness-related ones. A necessary step to achieve this main goal is to study noise annoyance due to road traffic noise in laboratory conditions. This step is based on a perceptual and cognitive typology of road traffic noise in urban areas [11].

The paper is then organized as follows. The perceptual and cognitive typology [11] is briefly described in a dedicated section. Then, the laboratory study of annoyance due to these perceptual categories is detailed, including method, results and a discussion. Finally the main conclusions are given.

2 A perceptual and cognitive typology of road traffic pass-by noises in urban areas [11]

Noise emission models that are used to generate noise maps are based on physical criteria (e.g. [12]). Three of them were crossed to build an *a priori* physical typology of road traffic noise in urban areas: (1) “vehicle type” detailed in buses, heavy, light, and two-wheeled vehicles, (2) “driving condition” detailed in acceleration, constant speed, and deceleration, (3) “road morphology”, detailed in U-shaped street and open street [11].

In order to assess the perceptual relevance of such a physical typology, 57 road traffic pass-by noises were extracted from *in situ* stereophonic recordings carried in the French city of Lyon. The recordings were made using ORTF technique (Schoeps MSTC 64 microphones, with Schoeps BBG windfields), and stored on a portable recorder (Tascam P2, sampled at 44.1 kHz with an amplitude resolution of 24 bits). The axis of the ORTF couple was placed perpendicularly to the road, at a height of 1,5 m and at least 2 m from any reflecting wall ([13]). The duration of the extracted pass-by noises (between 3s and 9s) was imposed so that pass-by noises (1) contain only auditory information relative to this pass-by noise, and (2) contain enough auditory information in order to allow their identification by listeners.

The 57 pass-by noises were submitted to a panel of subjects *via* a free categorization task associated to free verbalization. Such a procedure (cf. [14] for a description) is particularly adapted to the understanding of the psychological principles underlying the process of natural categorization [15, 16]. The interest is then to confront an organization chosen *a priori* with physical criteria, to the organization shared among listeners, in accordance to their previous sensory experiences. The analyses carried out (statistical analysis of the free categorization, and linguistic analysis of the free verbalization [11]) resulted in the proposal of a perceptual and cognitive typology made up of 7 categories of vehicle pass-by noises. The 7 categories are mainly structured by the *a priori* “vehicle type” and “driving condition” criteria (cf. first column of Table 1), inferred by the subjects from the acoustic properties of the stimuli. The other criterion “road morphology” did not play a significant role in the categorization process. Acceptability or negative judgments were made on pass-by noises, and linked to spectral and temporal aspects of pass-by noises.

Then 14 selected pass-by noises were submitted to another panel of subjects *via* a dissimilarity test using the pairwise comparison method. The aim of this experiment was to test the robustness of the proposed perceptual and cognitive typology. The statistical analyses carried out on the dissimilarity judgments, led to the scaling of the 14 pass-by noises in a 2-dimensional perceptual space. The first dimension of this space was explained by 2 indices describing temporal aspects that are involved in the different driving conditions: roughness R (related to the periodic evolution of the temporal envelope), and SPL growth rate in time (related to global temporal evolution). The second dimension of the space was linked to a spectral index involved in the identification of the different vehicles: L_{MF} (the A-weighted equivalent sound pressure level between third octave bands centered on 315 and 1250 Hz).

The confrontation of both experiment results supported the proposal of the perceptual and cognitive typology. The criterion “vehicle type” seems to be a categorical criterion linked to sound identification, and explained by a spectral index describing the dissimilarity between vehicle types. The criterion “driving condition” seems to be a continuous criterion explained by a variation of temporal indices describing periodic evolution of the temporal envelope and global temporal evolution.

3 Noise annoyance indicators for the 7 perceptual and cognitive categories

In accordance to our main goal, each category of the perceptual and cognitive typology of road traffic pass-by noises is studied separately from the noise annoyance point of view in laboratory conditions.

Thus 7 listening tests are set up.

3.1 Method

3.1.1 Stimuli

The objective of this experiment is to define noise annoyance indicators that are able to take into account acoustical factors that are complementary to loudness-related ones.

Consequently, 4 or 5 pass-by noises (depending on the category) are selected, from the more representative to the less representative noises in each category [11]. The pass-by noises are then set at 7 different $L_{A,eq,T}$: from 50 to 62 dB(A), in 2 dB(A) steps. This range is chosen in order to comply with the one observed during an *in situ* study [17], to which our results would be confronted in a further step.

Consequently, two main factors are involved in this laboratory study: “Noise Level” and “Noise Source”, with respectively 4 (or 5) and 7 modalities, resulting in 28 (or 35) stimuli depending on the category studied (cf. Table 1).

According to previous studies on noise annoyance in laboratory conditions, stimuli duration has a limited influence on short-term noise annoyance (e.g. [18, 19]). Consequently, the original duration of pass-by noises (between 3s and 9s) is kept.

Moreover, the worst case of noise exposure is considered in this study, i.e. home windows wide open, or being in private outdoor spaces. It means that no correction is applied to the stimuli in order to simulate façades or windows. In fact, façade and window types may have an influence on auditory judgments [20, 21], and the choice of one particular filter may thus have led to a particular case.

3.1.2 Apparatus

The experiment is computer controlled using Matlab© scripts. It takes place in a quiet room, with a background noise measured at 19 dB(A).

The reproduction of stimuli is stereophonic using a 2.1 system: 2 Dynaudio Acoustics BM5A Active loudspeakers are associated to a Dynaudio Acoustics BM9S subwoofer.

According to Bech and Zacharov recommendations [22], the subject faces the loudspeakers placed at a 1,20 m height, and these latter form an equilateral triangle with the center of the subject’s interaural axis.

Table 1: Stimuli for the study of annoyance in laboratory conditions.

Category	Nbr of selected pass-by noises	dB(A) range	Nbr of stimuli
1: Two wheeled vehicles at constant speed (6 pass-by noises)	5	50 to 62 In 2 dB(A) steps	35
2: Two wheeled vehicles in acceleration (6 pass-by noises)	5		35
3: Buses, heavy and light vehicles at constant speed (14 pass-by noises)	5		35
4: Two-wheeled vehicles in deceleration (4 pass-by noises)	4		28
5: buses, heavy and light vehicles in deceleration (13 pass-by noises)	5		35
6: light vehicles in acceleration (4 pass-by noises)	4		28
7: buses and heavy vehicles in acceleration (10 pass-by noises)	5		35

3.1.3 Procedure

Annoyance is understood as short-term annoyance, as experienced in an imaginary situation [23]. The subjects are asked to imagine themselves at home while doing a relaxing activity they are used to (e.g. reading, having a conversation, watching TV, etc.).

The stimuli are presented one by one in random order and the scaling method is adapted from ISO 15666:2003 standard [24]. Subjects are asked to assess noise annoyance using a continuous scale with numerical labels equally spaced from 0 to 10 and 5 verbal labels (from “not at all”, “slightly”, “moderately”, “very” to “extremely”) to facilitate the use of the continuous scale.

3.1.4 Subjects

Thirty subjects participated in each listening test (on average 19 men and 11 women, between 18 and 60 years old). They were paid for their participation.

The subjects involved in several listening tests participated on separate days.

Each listening test lasted around 20 minutes.

3.2 Results

3.2.1 Effects of main factors

In order to investigate the effects of main factors ("Noise Level", and "Noise Source") on annoyance responses, two-way ANOVA with repeated measures are carried out for each listening test.

Unsurprisingly, the main factor "Noise Level" has a significant effect on the annoyance responses due to each category of pass-by noises. This factor explains between 43% and 60% of the variance in annoyance responses [25], respectively due to pass-by noises of category 2 (two-wheeled vehicles in acceleration), and pass-by noises of category 1 (two-wheeled vehicles at constant speed). For all the categories of vehicle pass-by noises, annoyance responses significantly increase with increasing SPL values.

The main factor "Noise Source" has no significant effect on annoyance responses due to pass-by noises of category 1, and has a significant effect on the annoyance responses due to pass-by noises of the other 6 categories. For these latter, this main factor explains from 13% to 34% of the variance in annoyance responses respectively due to pass-by noises of category 5 (buses, heavy vehicles and light vehicles in deceleration), and of category 2. These results show that within all perceptual and cognitive categories (except category 1), there is more or less heterogeneity between pass-by noises from the annoyance point of view. This is illustrated on Figure 1, taking the example of pass-by noises of category 2 (high heterogeneity), and category 7 (low heterogeneity). The duration of each pass-by noise is also indicated. Examining the groups of significantly different pass-by noises (from the annoyance response point of view) along with the duration of each pass-by noise, it is seen that durations involved in these experiments were not a priority criterion to formulate annoyance judgments.

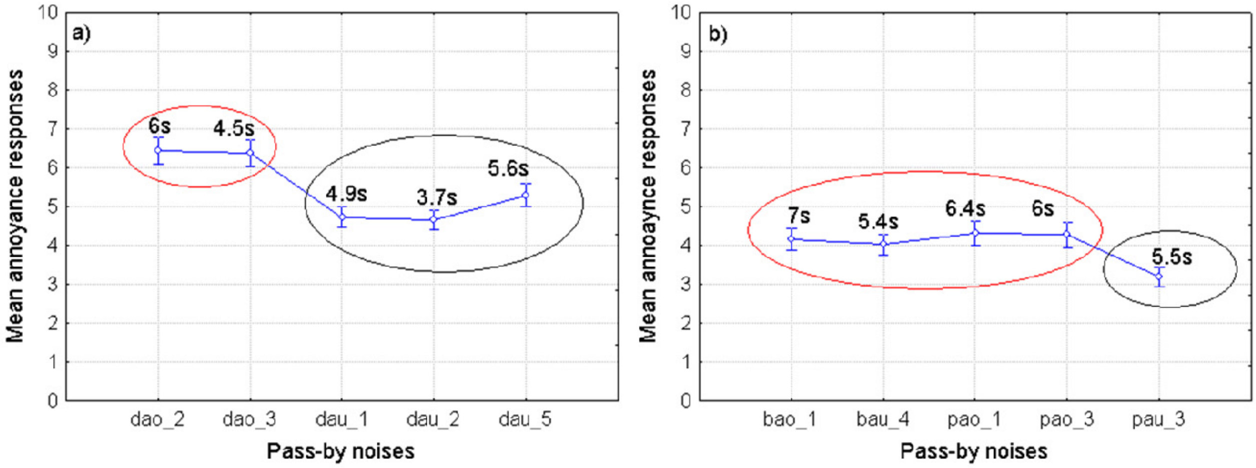

Figure 1: Effect of the main factor "Noise Source" for 2 perceptual categories with more or less heterogeneity within their pass-by noises. Pass-by noises which cause non significantly different annoyance responses (HSD Tuckey) are circled. a) category 2 (two-wheeled vehicles in acceleration). b) category 7 (buses and heavy vehicles in acceleration). Error bars around mean values represent standard error.

Table 2: Noise annoyance indicators for the perceptual categories of road vehicle pass-by noises. R^2 (or r^2) is the coefficient of determination. Std. err. is the standard error of the estimate. ^{b}: $p<0.05$; ^{c}: $p<0.01$; ^{d}: $p<0.001$

Cat.	Regression equations for the proposed indicators	R^2 (or r^2)	Std. Err.
1	$A_1 = 1.03N^d + 0.18$	0.95^d	0.32
2	$A_2 = 16.99N_{15\text{-}18}{}^d + 0.10F^d + 1.45$	0.92^d	0.37
3	$A_3 = 1.32N^d – 0.32\Delta N^{-d} - 0.35$	0.97^d	0.23
4	$A_4 = 0.88N^d + 0.02R_{max}{}^b + 0.33$	0.96^d	0.29
5	$A_5 = 1.06N^d + 0.08F_{max}{}^d – 1$	0.95^d	0.34
6	$A_6 = 0.29L_{MF}{}^d – 8.48$	0.95^d	0.34
7	$A_7 = 0.95N^d + 0.10F^c – 0.51$	0.94^d	0.34

3.2.2 Annoyance indicators for the 7 categories

The effect of main factors on annoyance responses due to the 7 categories was highlighted. The next step is then to find indices that are able to take into account these effects and *in fine* constitute the proposed indicators. Thus correlation analyses are led between mean annoyance responses and the values of various acoustic and psychoacoustic indices. Then simple (or multiple) linear regression analyses follow.

a. Category 1: loudness

Annoyance responses due to pass-by noises of category 1 are significantly influenced only by the main factor “Noise Level”. Thus only indices that are loudness-related are investigated.

From the indices considered (e.g. $L_{Aeq,T}$, $L_{Ceq,T}$, L_{Amax}), Zwicker’s loudness is proposed to constitute the annoyance indicator. The regression analysis reveals a high coefficient of determination R^2 (cf. Table 2).

b. Category 2: loudness, spectral specificities and temporal envelope

The results of the two-way ANOVA with repeated measures carried out on the annoyance responses due to the pass-by noises of category 2 lead us to search indices that are able to take into account the highlighted effects.

Two of these considered indices were found to explain adequately these variations: $N_{15\text{-}18}$ (Zwicker’s loudness integrated between Barks 15 and 18), and F (the mean fluctuation strength). The first index allows characterizing loudness and the energy content in high frequencies, characteristic of two-wheeled vehicles. The second index is related to a sensation produced by quick and periodic temporal changes [26], which in fact are related to the engine noise predominant in urban areas especially at limited speed and in acceleration. The proposed indicator associating both indices, results in a high R^2 (cf. Table 2).

c. Category 3: loudness and temporal evolution

In order to explain the factor “Noise Level”, the Zwicker’s loudness N appears superior than the index $L_{Aeq,T}$ (respectively r=0.98; p<0.001 and r<0.93; p<0.001). The factor “Noise Source” is explained by an index describing the temporal evolution. This index called the decrease rate of loudness in time (denoted ΔN^-) is the slope of the regression line between time and the time-varying loudness, after the maximum loudness value is reached.

The proposed indicator links these indices to the mean annoyance responses and results in a high R^2 (cf. Table 2). For the pass-by noises of this category, at equal loudness, subjects found more annoying pass-by noise from vehicles that takes more time to go away.

d. Category 4, 5, 7: loudness and temporal envelope

For these categories, Zwicker’s loudness is again better correlated to mean annoyance responses than the index $L_{Aeq,T}$, thus it is chosen to explain the influence of the factor “Noise Level”. As for the factor “Noise Source”, it is mainly explained by indices describing the engine noise: R_{max} (maximum roughness) for category 4, F_{max} (maximum fluctuation strength) for category 5, and F for category 7. Roughness and fluctuation strength are similarly defined, the difference lies in the frequency of the amplitude modulation.

For these categories, the indicators proposed allow a good prediction of mean annoyance responses (cf. Table 2). For these categories, at an equal loudness, subjects found pass-by noises producing higher roughness or fluctuation strength more annoying.

d. Category 6: loudness and spectral specificities

For this category, the index L_{MF} (A-weighted SPL in middle frequency-bands [10]), shows the higher correlation with mean annoyance responses due to pass-by noises of category 6 (r=0.97; p<0.001). This index is able to take into account the influence of acoustic energy, and the influence of the spectral content which is related to the main factor “Noise Source”.

For the pass-by noises of category 6, the more important the spectral content in middle-frequencies, the more annoying the pass-by noises were judged by the subjects.

3.2.3 Discussion

The indicators proposed to characterize the annoyance due to the pass-by noises of each category of the perceptual and cognitive typology are consistent with the verbal descriptions given in the free verbalization task [11]. For example, pass-by noises of category 2 were judged to be “more strident”, and “much more high-pitched” than pass-by noises of other categories. The indicator proposed for category 2 includes the index $N_{15\text{-}18}$, which accounts for this specific high-frequency content.

It is found that the strong influence of the main factor “Noise Level”, is for all the categories equally or better explained by the Zwicker’s loudness N (or an index constructed from N) than by the index $L_{Aeq,T}$. This is in agreement with Nilsson’s result [9], and suggests examining the opportunity to use loudness to characterize environmental noise.

In this paper, noise annoyance is studied for the different categories separately. Morel *et al.* [11] made the assumption that in urban areas any road traffic may be composed of a certain number of the pass-by noises involved in the different categories. Thus in a next step it would be interesting to study annoyance due to such reconstituted road traffic, and consequently to assess the efficiency of the proposed indictors. As a matter of fact, Berglund and Nilsson [27] found that overall traffic annoyance responses collected *in situ* are dependent on the on-time of vehicle types.

4 Conclusion

The main goal of the work presented in this paper was to contribute to an improvement of noise maps through the proposal of annoyance indicators that are more meaningful from the individual point of view. To do so, annoyance due to each of the 7 perceptual and cognitive categories of vehicle pass-by noises proposed in a previous paper was assessed in laboratory conditions. The main conclusions are as follows:

- Noise level as well as differences between pass-by noises within categories lead to significant variations in annoyance responses;
- The proposed noise annoyance indicators associate an index based on Zwicker’s loudness to an index describing temporal aspects, which cannot be taken into account by the widely used $L_{Aeq,T}$. For category 6, the spectral content in middle frequencies is relevant to predict annoyance;

- The temporal indices are linked to different aspects: either the global temporal evolution (category 3), or the variation of the temporal envelope (categories 2, 4, 5, 7).

A next step of this work would be to test these indicators in case of noise annoyance due to reconstituted road traffic.

Acknowledgments

The authors would like to thank ADEME (the French Environment and Energy Management Agency), who partly funded this work (contract n°0866C0066).

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