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## Urban acoustic imaging : from measurement to the soundscape perception evaluation

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### ABSTRACT

Characterising the urban sonic environment is usually done by measuring the energetic indicators such as the average A-weighted level. The European 2002/49/EC directive compels large cities to establish noise maps and pursue action plans aimed at reducing the percentage of citizens exposed to excessive noise levels. In parallel the soundscape concept introduced by Raymond Murray Schafer aims to quantify the urban sonic environment with a global approach taking into account the nature of sources, the context of listening or the habituation.

In a complementary approach, our work seeks to quantify the urban soundscape locally using acoustic level maps produced using antennas with a very large number of microphones (up to 256). This method seeks to detect and locate the numerous sources potentially present in the area of interest, but also to assess their instantaneous and averaged acoustic level and spectrum. This paper presents the experimental set-up implementing acoustic arrays based on digital MEMS microphones together with their digital recording system. We present the analysis of a benchmarking campaign led to build a database characterizing various vehicles in different urban-like scenarios. Finally, we investigate new methods so as to combine these objective data and improved annoyance models.

### 1. INTRODUCTION

The European directive 2002/49/CE [1] requires from large cities the creation of strategic noise maps and action plans. Therefore, local governments have to invest in improving the sonic environment in their city. Besides regulation outcomes, the development of eco-neighborhoods shows the growing interest of city dwellers themselves to improve the quality of their urban environment. Standard noise maps provide tangible information but have several limitations. Firstly they distinguish between different sources of noise (road, rail, aircraft or industrial) instead of providing a global information secondly, the noise exposure is averaged over the time.

The Harmonica project [2] proposed a new index to evaluate the sonic environment. It is based on the A-weighted level variation over time and consists of two sub-indices: the background noise (BGN) and the occurrence of sound events (EVT). The summation of these two indices ranges from 0 to 10. Mietlicki *et al.* [2] showed that there is a good agreement between the index value and the city dwellers feeling. Such as Marquis-Favre *et al.* [3], Mietlicki *et al.* [2] showed that the perceived annoyance cannot be properly evaluated through the sole averaged A-weighted SPL. These results enforce Schafer's point of view. Indeed, he writes [4] that "*Only an overall assessment of the acoustic environment can give us the means to improve the sound orchestration of the world*" and proposes to focus on determining whether the sound is annoying or pleasant in the so called *soundscape* before thinking of reducing its intensity. He added that "*the best legislation against the noise in our time will be the one that will bring together quantitative and qualitative dispositions*". Hiramatsu [5] confirms the interest of the soundscape approach in relation to the noise maps expressed in  $L_{den}$ . He insists on the fact that sound source identification and sound event detection give a more holistic information.

In all those approaches analysing the sound sources is a key point. It seems essential to be able to distinguish all the individual sound sources in a complex sound scene and analyse them.

Our approach consists in carrying out the identification and quantification of noise sources in the city from acoustic imaging techniques. Noise annoyance caused by these sources is studied afterwards through

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existing annoyance models. The issue of summation of the specific annoyances induced by each source is raised to quantify the overall annoyance of the studied sound scene.

Section 2. describes the current state of consideration of noise pollution in public policies. It also makes an overview of some models found in the literature to describe the perceived annoyance. In section 3. we present a method using an acoustic antenna for the diagnosis of a local soundscape. Finally, in section 4. we investigate the integration of the data processed from acoustic imaging in noise annoyance model.

## 2. PERCEPTION OF THE URBAN SONIC ENVIRONMENT

For almost a century the decibel has been used to quantify noise events in order to properly account human perception. This scale is based on the psycho-physic law of Weber-Fechner which describes the relation between a perceived sensory stimulus and the excitation as a logarithmic law. Later frequency weighting functions were introduced and used to filter the measured signals according to the ear frequency response function and provide measurements closer to the perceived SPL.

The European Directive 2002/49/CE [1] introduced a new metric: the day, evening, night level ( $L_{den}$ ). It aims to relate the feeling that a sound is perceived more annoying in the evening and during the night. Therefore the evening level is increased by 5 dB and the night level by 10 dB. It is processed from A weighted levels and writes :

$$L_{den} = 10 \log \left[ \frac{12}{24} \cdot 10^{L_d/10} + \frac{4}{24} \cdot 10^{(L_e+5)/10} + \frac{8}{24} \cdot 10^{(L_n+10)/10} \right] \quad (\text{dBA}), \quad (1)$$

where  $L_d$  is the daytime level (from 6 am to 6 pm),  $L_e$  is the evening level (from 6 pm to 10 pm) and  $L_n$  is the level measured during the night (from 10 pm to 6 am).

The same EU directive introduced the obligation for cities (over 100,000 inhabitants) to create noise maps in  $L_{den}$ . It is a simple and efficient communication tool but it has some limits. Firstly, these maps are generally created considering specific sources (road traffic, rail traffic, air traffic, industrial noise, ...) instead of overall noises, which does not allow to understand the global exposure to noise. Secondly, the sounds are considered only as nuisances hence excluding potential positive perceptive characteristics.

### 2.1 The *soundscape* concept

In the early 1970's, Raymond Murray Schafer [4] introduced the *soundscape* concept founded on the idea that the surrounding sounds should not always be considered negatively, that they can be harmonious. He insists on the importance to recover the harmony of sounds in big cities. This concept aims to analyse the sonic environment globally, considering the nature of sounds, the listening context or the habituation to the sonic environment.

In the efforts of describing the soundscape, the notion of sound source is fundamental and each one is defined and quantified with a subjective level or a verbalisation. In this context, an example of cartography of the soundscape can be the one realised by HONG and JEON [6]. They propose to create maps evaluating subjectively three types of noise : road traffic noise, human sounds and natural sounds. The subjective levels range from 1 ("do not hear at all") to 5 ("dominates completely"). The maps are created from the evaluations provided by investigators scanning the area of interest according to a predefined mesh. A final interpolation process is used to smooth the maps.

The soundscape concept is based on the segregation of sound sources in order to select the ones to be kept (such as natural noise) and those to be reduced (the annoying ones). That is why a sound source description tool must be designed in order to quantify their specific induced annoyance. Finally our study aims at creating noise annoyance maps and provide the residents an effective tool regarding noise exposure.

### 2.2 Noise annoyance models

As part of the soundscape concept, the characterization of sound sources in their environment, in terms of annoyance, is a prerequisite to any soundscape study.

Noise annoyance has been defined by Guski *et al.* [7] as the "*relation between an acoustic situation and a person who is forced by noise to do things he/she does not want to do*". For instance, we can be accustomed to a constant noise from a major traffic artery under our windows whereas we would be annoyed by a horn suddenly emerging while reading a book.

Noise annoyances models aim to link the perceived annoyance with measurable physical quantities for each isolated source (specific annoyance) and for the entire sound scene (total annoyance). For the latter, there is no consensus in the literature about the best solution for combining the specific annoyances. However both the dominant source model and the independent effects model [8] are in good agreement with the perceived annoyance [9].

A particularly interesting noise annoyance model has been proposed by MOREL *et al.* [10]. This model is based on previous works [11, 12] highlighting the possibility of reducing the road traffic diversity into seven perceptive categories. Each category consists of different kinds of vehicles in the same driving configuration (acceleration, deceleration, constant speed). For instance, category number 3 contains buses, heavy and light vehicles passing-by at constant speed. The authors provide a model (summarized figure 1) based on combining energetic and psychoacoustic quantities of a sound source on the vehicle to assess the specific noise annoyance induced by the vehicle. For this specific category the authors have measured a significant influence of the “noise level” factor which is better described by the loudness (denoted  $N$ ) computed with the Zwicker’s model [13] than with the equivalent noise level  $L_{Aeq}$ . For each category, the annoyance is modelled combining the relevant energetic or psychoacoustic indices. The coefficients of the linear combinations are obtained by linear regression of the expressed experimental annoyances. Finally the specific annoyance associated to the category number 3 can be processed according to the following relation :

$$A = 1,32 N - 0,32 \Delta N^- - 0,36 \quad , \quad (2)$$

where  $\Delta N^-$  is the loudness decrease rate over the time.

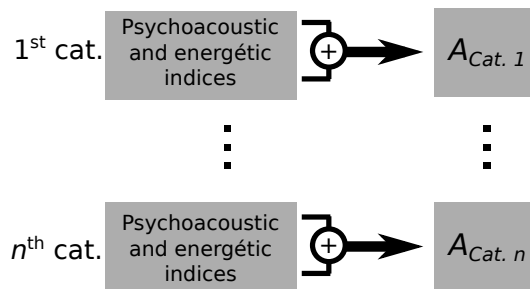


Figure 1 – Morel *et al.* [10] model principle

These linear annoyance models require the knowledge of the physical characteristics of the noise sources. Acoustic imaging uses microphones antennas to produce sound pressure map. From these maps, it is possible to retrieve spectral, temporal and spatial informations on the sources of noise and *in fine* perform an automatic local description of the local soundscape.

### 3. SET-UP AND METHOD OF THE ACOUSTIC IMAGING

Most of the existing acoustic imaging systems use analogical microphones which means a cumbersome conditioning circuitry for each channel and a heavy experimental set-up. The Megamicros acquisition system is based on digital MEMS (Micro Electronic and Mechanical System) microphones. For now, the system can manage arrays of 256 sensors (1024 in the next future) scattered over a large area (typically a few tens of meters).

#### 3.1 The acoustic system

The MEMS microphone chips (ADMP441) integrate conditioning circuitry and A/D conversion reducing the overall size of the system. The microphones are omnidirectional and have a flat frequency response between 60 and 15,000 Hz. The details of the system are presented by Vanwysberghe *et al.* [14]. In addition to the 256 MEMS microphones, the Megamicros system handles 4 analogical channels but also logical channels for the acquisition synchronization. The low power consumption allows the system power supply using batteries which gives it great autonomy. The use of long RJ45 cables (10 meters) enables the deployment of a large variety of geometries. For the pass-by measurements used in our study a 19.6 m long, 2.25 m height antenna was deployed.

#### 3.2 Imaging method

Our study has two complementary objectives both using conventional beamforming with suitable antennas. First, at the scale of the vehicle, it is to locate noise sources and identify them in terms of temporal variations, spectrum and directivity in representative scenarios of the urban road traffic. Second, at street scale, we want to quantify the overall annoyance caused by traffic combining many sources.

##### 3.2.1 The vehicle scale

Figure 2 presents the experimental set-up used on the site of La Ferte-Vidame provided by PSA Peugeot Citroen in January 2016. These tests were carried out based on the recommendations of ISO 362

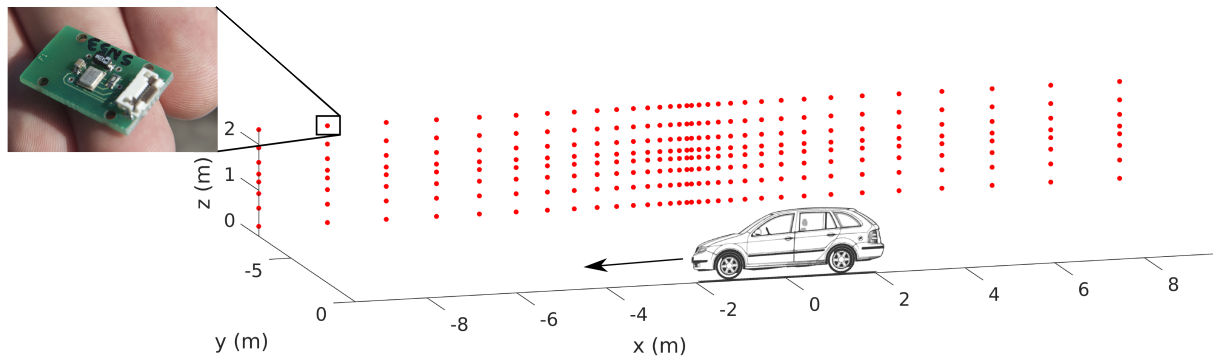


Figure 2 – Experimental set-up for pass-by measurements - Array of 256 microphones (red dots) and picture of an elementary MEMS microphone and circuit.

for the evaluation of vehicle pass-by noise. The microphone array is located at 7.5 m of the vehicle path. However the tests are adapted to take into account the specificity of urban traffic.

The aim of these measurements is to build a database of acoustic sources representative urban driving conditions. These sources are to be identified later on at street scale.

For each vehicle under test (see table 1) the following scenarios have been recorded :

- 25 km/h constant speed in second gear (round-trip, engine on and off);
- 50 km/h constant speed in third gear (round-trip, engine on and off);
- traffic light simulation : deceleration from 30 to 0 km/h, engine idle in front of the centre of the antenna, then acceleration from 0 to 30 km/h with gear change (round-trip);
- full throttle acceleration along the 20 m of the antenna (round-trip)

The tested vehicles present various characteristics in terms of power energy type and range. They are listed in table 1.

Table 1 – Characteristic of the vehicles used during the tests.

Vehicle's model	Energy	Cylinders	Range
Citroën C4	diesel	4 cyl.	saloon
Citroën DS3	gasoline	3 cyl.	urban
Peugeot Ion	electric		urban
Citroën Picasso	diesel	4 cyl.	minivan
Renault Laguna	diesel	4 cyl.	saloon
Yveco Daily	diesel	4 cyl.	commercial
Peugeot E-Vivacity	electric		scooter
Peugeot Speedfight	gasoline	50 cm <sup>3</sup> , 2 temps	scooter
Peugeot Metropolis	gasoline	400 cm <sup>3</sup> , 4 temps	scooter

In order to establish the feasibility of moving sources localization, a preliminary experiment was led. A controlled sound source emitting a 2 kHz harmonic signal is placed at the level of the front passenger window in a car moving at 20 km/h. The figure 3 shows the resulting acoustic image. The beamformed acoustic energy is integrated from 1970 to 2030 Hz in order to get rid of the Doppler effect. Each image is calculated on a 100 ms frame in order to limit the width of the main lobe. Nevertheless, the resolution is degraded due to the target displacement (50 cm) for the duration of the frame. The colour scale dynamics limited to 3 dB enables to evaluate the resolution to about 0.6 m. The capabilities of the system in terms of localization, resolution and SPL evaluation validates the setup for further investigations.

Braun *et al.* [16] sought to characterize the spectra of the sources of noise produced by light heat engine vehicles. They show that an acoustic image integrated over the 500 Hz octave band assesses the contribution of the main sources of noise (engine and pneumatics). Figure 4a shows such an image for a light heat engine vehicle (a Citroen C4 diesel) at 25 km/h constant speed. It exhibits the major contribution of the tire/road contact (measured at 63 dB) and of the engine (measured at 68 dB) which are the sources reported in the literature for the same scenario [16].

Figure 4b shows the result for a pass-by measurement at the same speed but with the engine switched off entering the test zone. Two main sources are detected: the tire/road contacts. They are measured at the same level as previously *i.e.* 63 dB.

Those results give us some elements of the sound sources database which to be used in the analysis of the urban road traffic and detect the perceptible category of vehicles passing by. The following process

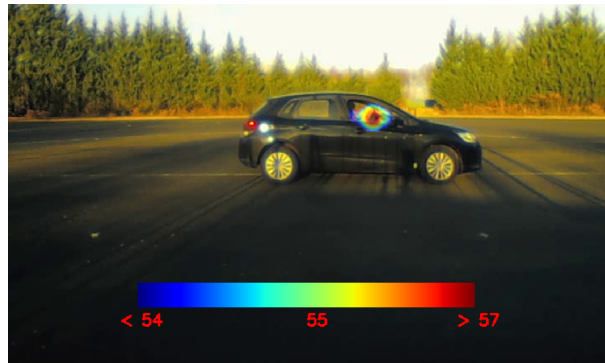


Figure 3 – Localisation of a controlled source moving at 20 km/h emitting a 2 kHz harmonic signal - Integration over 4% of the 2 kHz octave band - Dynamic range : 3 dB.

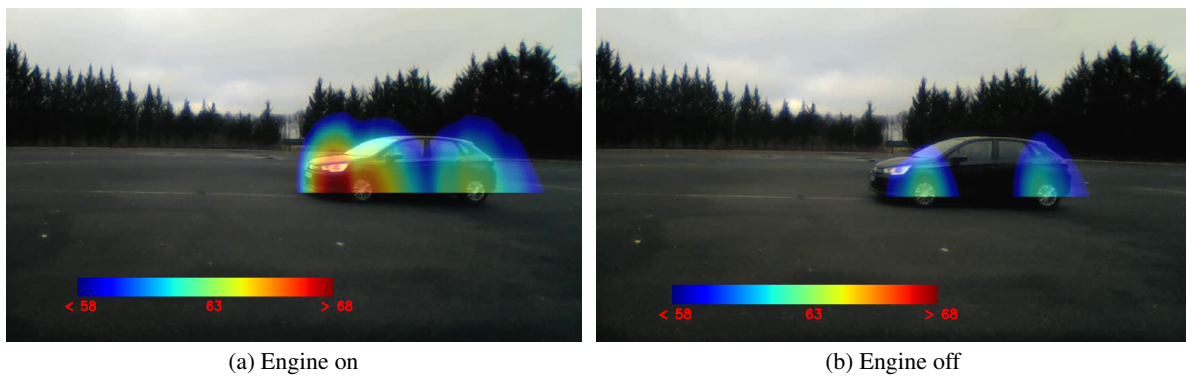


Figure 4 – Acoustic image integrated over the octave band of 500 Hz - Citroën C4 - 25 km/h - stabilised speed - Dynamic range : 10 dB.

relying on the perceptive categories combining energetic and psychoacoustic quantities finally provides an estimate of the specific noise annoyance.

### 3.2.2 The street scale

The following experiment used the signals of a 22 m long linear antenna with 128 MEMS linearly spaced by 17 cm. The antenna is located at 9 m in height with a view on 4-way urban axis (see Figure 5a and 5b) and near a traffic light. On this axis, the traffic alternates between constant speed, stops, starts and acceleration. Thanks to this device, it is possible to produce images with a good longitudinal resolution. However, in the transverse direction, the sources are less discriminated. The images presented here are built on a 125 ms frame (integration time of sound level meters) and the acoustic energy is integrated over the 1 kHz octave band.

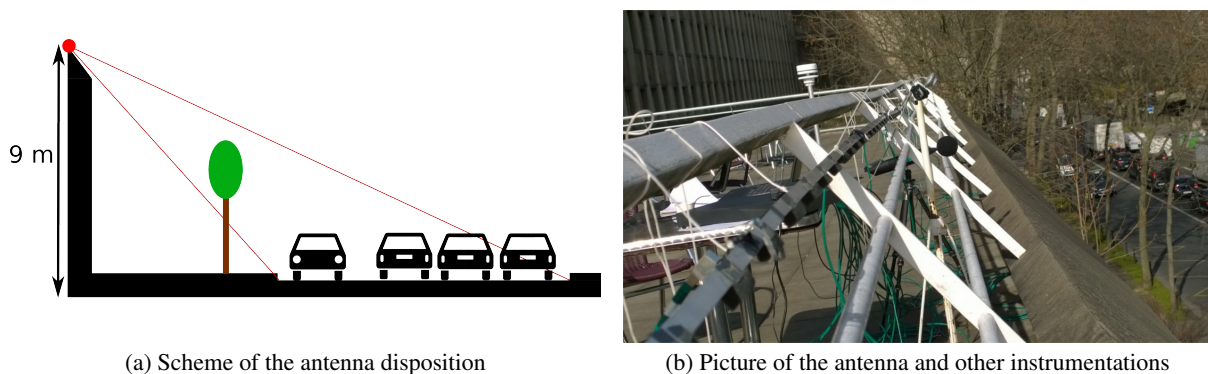


Figure 5 – 128 microphones antenna for urban acoustic imaging

The figure 6a shows the acoustic image obtained when a truck starts. The engine and exhaust system are the main sources of radiation. We can notice the mask of the car passing in the same beam, behind the truck. Note that this masking effect can also be noticed when listening a microphone signal. Figure 6b

shows the image obtained on the passage of a small commercial vehicle passing-by at constant speed. As previously in the case of isolated vehicles the tire/road contact shows to be the predominant source.

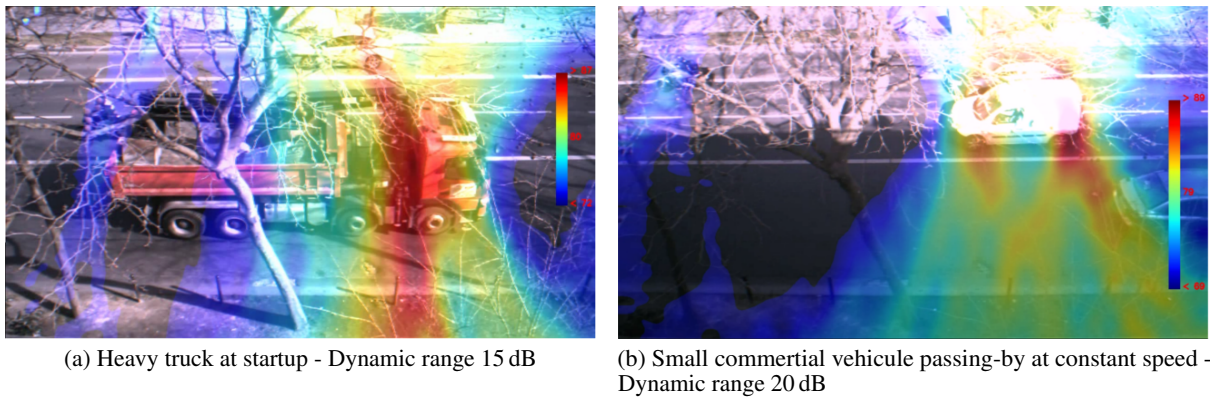


Figure 6 – Acoustic image on the Saint Bernard dock in Paris - Octave band of 1000 Hz.

#### 4. DISCUSSION

Our goal is to use microphone arrays and acoustic imaging to provide the data needed by annoyance models. Preliminary results of acoustic imaging show the feasibility of the methodology proposed and summarized in figure 7 :

- identify the sources at the vehicle's scale ;
- thanks to a sound source database and image processing, identify the vehicle type and it's driving condition in terms of Morel's perceptive categories;
- implement the Morel *et al.* model for specific annoyance for each vehicle of the sound scene;
- Compute the total annoyance for the studied sound scenes.

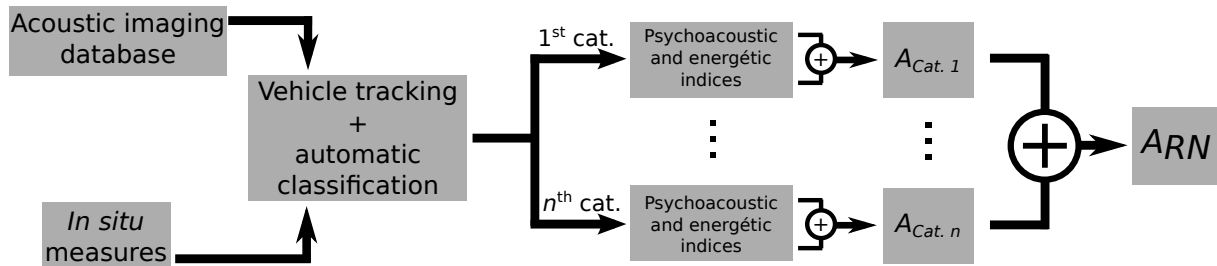


Figure 7 – Schematic diagram of adapting the model Morel *et al.* [10] with the data coming from the Megamicros system. With  $A_{RN}$  the total road traffic annoyance et  $A_{cat. n}$  the specific annoyance of the  $n^{\text{th}}$  vehicle category.

#### 5. CONCLUSIONS

The goal of the work is to provide an effective tool based on acoustic imaging combined to a psychoacoustic model to evaluate the noise annoyance.

Experiments were conducted using large acoustic arrays developed as part of the Megamicros project. They have allowed to distinguish the noise sources on the road vehicles for representatives situations of the road traffic in European cities. Physical quantities characterizing the sources such as SPL and spectral support can be extracted. They are used in the following to determine perceptive categories according to Morel's psychoacoustic model.

Furthermore, large microphones array were installed in Paris in order to measure the acoustic and energetic indices for each vehicle in the traffic. This will allow to use an annoyance model and quantify the annoyance induced by each vehicle and thus obtain the total annoyance induced by the road traffic in the street.

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