# INNOVATIVE APPROACH TO QUANTIFY AND QUALIFY THE REAL TRAFFIC NOISE POLLUTION

**Kévin Cormier (1), Florent Masson (1) and Patrice Pischedda(2)**

(1) ACOEM France,200 chemin des Ormeaux, 69570 Limonest France
Kevin.cormier@acoem.com / Florent.masson@acoem.com

(2) ACOEM Asia, 104 Soi Pradit Manutham, Bangkok 10230

patrice.pischedda@acoem.com

## ABSTRACT

Many pathologies, such as sleep problems, fatigue, stress and the increased risk of heart disease are associated with traffic noise and in particular with noise peaks generated by certain excessively loud vehicles which are added to the continuous traffic noise. Methodologies used for the development of action plans against noise pollution - as they are based on analysis on equivalent noise levels averaged over long periods of observation - do not fully take this dimension of the health problem into account. Vehicle pass-by noise measurement in real traffic conditions is now possible thanks to the use of environmental sensors that combine measurement of the sound level and localization of the predominant source of noise at any time. The use of such sensors enables the automatic detection of noise coming from a vehicle. It means that the road noise contribution can be precisely and constantly extracted from the ambient noise. Furthermore, precise acoustic characteristics of every noise event linked with the pass-by of certain vehicles (or with certain drivers' behaviour) are accessible. The noisy vehicles can be automatically pointed out. After a quick presentation of the prototype used for several tests in real conditions this paper presents how such rich traffic noise data can be used for noise pollution management, either to prevent or appoint responsibilities. The results exposed in this document are widely based on the ongoing experiment sponsored by the French minister of ecology in the frame of the Mobility Act promulgated in 2019.

## CONTEXT

On March 14, 2020, the European Environment Agency published its periodic updated noise report: Environmental noise in Europe (EEA Report No 22/2019) [1].

In line with previous findings, namely - Noise in Europe (2014) and Quiet areas in Europe — The environment unaffected by noise pollution (2016) - this report reaffirms the endemic nature of noise pollution on the scale of the European continent, it publishes a quantified assessment of people exposed to noise by source typology.

Thus, from the very first sentence of the executive summary, the diagnosis is brutal: *"Long-term exposure to environmental noise is estimated to cause 12,000 premature deaths and contribute to 48,000 new cases of ischaemic heart disease per year in the European territory. It is estimated that 22 million people suffer chronic high annoyance and 6.5 million people suffer chronic high sleep disturbance"*.

The findings are clear and the figures tally with the various opinion polls carried out by noise observatories in European capitals.
Take the example of CREDOC/BruitParif study of 2016 and recently updated in 2021 [2].

Noise Pollution is number 4 in terms of greatest inconvenience due to living in the Paris region. Just after the cost of living, insecurity and air quality. In 5 years, noise has gained 10 points in terms of concern for Ile-de-France residents and has overtaken mobility issues. Those who have already experienced traffic problems in Paris know it: it is not nothing!

Transport noise is the most frequently cited noise nuisance. Sources of noise related to road traffic occupy the first three places in the ranking: motorcycles, horns and the pass-by noise from passenger cars. Noise pollution related to air and rail transport appears in this ranking respectively in 4th and 6th position.

Here too, the perception surveys and the official European Union report agree: "*Environmental noise, and in particular road traffic noise remains a major environmental problem affecting the health and well-being of millions of people in Europe"* [1].

The consolidated conclusions of the European Environment Agency are regularly confirmed by field surveys. If this conclusion is reassuring it is not obvious. Indeed, the EU's periodic report Environmental noise in Europe — 2020 carried out in accordance with *Environmental noise guidelines for the European region*

*(2018*) considers as reference indicator the energy indicator $L_{den}$ only.

However, the perception that people have of their sound environment depends as much on the repetitive nature of sound events and their emergence from the background noise as on the intensity of the noise integrated and averaged over a certain period of time. Numerous studies and research have demonstrated this phenomenon. Among other examples, let us cite the work carried out within the framework of the European project Harmonica.

The $L_{den}$ is therefore sufficient to draw up a reliable macro observation, it shows it is limited to guide an effective policy adapted to the local situation.

In recent studies, some indicators such as the percentile $L_{50}$ have shown to be best correlated with sound perception of an urban soundscape [3].

The public authorities are taking on the dimension of the problem, particularly in France. According to ADEME (Agency for Ecological Transition) noise affects 9 million people and the social cost is estimated to 57 billion euros per year, including more than 20.6 billion for transport noise alone.

It is in this respect that the problems of noise pollution have been integrated into the French mobility orientation law, published in the Official Journal on December 26th, 2019. This law profoundly transforms mobility policy, with a simple objective: easier, cheaper and cleaner every-day transport [4].

The recognition by law of noise pollution and in particular the consideration of noise peaks is a real step forward and a lever to better prevent and fight against transport noise. Thus, article 92 of the mobility orientation law (LOM 92) deals specifically with road transport noise peaks and notably introduced the experimentation of automatic control of vehicle sound emission levels by acoustic radars.

## FRAMEWORK OF THE EXPERIMENT

This article 92 of the mobility orientation law specifies that the French government is interested in starting an experimentation for the observation of vehicle noise emission levels by fixed and mobile automatic control devices. Since the beginning of this project started in 2020 different evaluations have been performed in controlled environments (track test) and in several non-controlled environments (urban and suburban areas).

It is within the framework of this law that an organism of the French government composed by technical experts, called CEREMA, aims to evaluate prototypes proposed by manufacturers for the automated control of vehicle sound levels. ACOEM is positioned as one of these manufacturers with its device called Noise Radar (NR).

To realize an automatic system several elements have been defined by the CEREMA in order to provide a legal framework for experimentation. The following section exposes the main specific terminology and methodology used in this document and for the experimentation.

### Pass-by noise definition

Pass-by noise is the maximum of the total noise emitted by a vehicle during the duration of a passage. The duration of a passage corresponds to the duration of the presence of a vehicle in the detection zone defined for our system as a monitoring zone of -10 m to + 10 m on both sides. The pass-by noise terminology is taken from regulation No. 51-03 from UN [5]. The sound pressure level of the noise of a vehicle when it passes in front of the NR is noted $L_{veh}$ in this document. This level is not constant during its passage time, the pass-by noise measured at the distance D of the NR corresponds then to the maximum of this indicator during the duration of the passage:

$$L_{veh}(D) = max \quad (L_{AFmax}(t)) \qquad (1)$$

The LAFmax then characterizes the sound pressure level of the vehicle. It corresponds to the maximum A-weighted sound level with fast time weighting, as described in several standards as NF EN 61672-1 and NF S31-110 [6, 7].

### Ambient Noise definition

Ambient noise is the total noise existing in a given situation during a given time interval. It is composed of the noise emitted by all near or distant sources, including pass-by noise of the vehicle of interest. The definition comes from standard NF S31-110 relating to the characterization and measurement of environmental noise [7].

The sound pressure level of ambient noise is characterized by the same indicator ($L_{AFmax}$) as for a vehicle. One of the difficulties in the framework of this project is to ensure that the sound pressure level of the other sources of noise emitted by all near or distance sources have negligible effects and that it is possible to extract the pass-by noise of a vehicle in a complex environment.

### Pass-by noise measurement

To make a pass-by noise estimation we can refer to the UN regulation No. 51-03 for noise emission regulation and to the ISO 362 and ISO 9645 standards for the measurement of noise emitted by accelerating road vehicles [5, 8, 9]. The reference receiver defined in UN regulation No. 51-03 is located 7.5 m horizontally from the centreline of the roadway and at a height of 1.2 m, corresponding to a reference distance of 7.6 m. However, not all the criterion of these standards will be under control since the devices for automatic control of the pass-by noise will not be installed in a controlled environment. For example, the reference distance of 7.6 m will not be respected as for the road surface defined by ISO 10844 [10]. It means that several measurement uncertainties will have to be considered and controlled during the measurement.

To limit the uncertainties on the ambient noise measurement a Class 1 sound level meter in compliance with NF EN 61672-1 standard has to be used [6]. The sound level meter must be configured to record the $L_{AFmax}$ with a period of 20 ms.

## Pass-by noise correction

The pass-by noise is measured at a distance D that can be variable between the system being evaluated and the vehicle considered according to the environment limitations and installation conditions. The system being also able to monitor different lanes, this distance between a vehicle and the reference distance of 7.6 m have to be corrected. This distance D takes into account the horizontal distance and the height difference and is corrected according to the geometric divergence of noise. The geometric correction $K_D$ is then defined using the following formula:

$$K_D = 20\log\left(\frac{D}{D\_0}\right)$$

With D_0 = 7.6 m (2)

It is then necessary to evaluate the distance between a vehicle and the NR. Since it is not possible to know exactly the position of the source of noise (there are in fact several in a vehicle) in the volume vehicle and that this measurement of the moment of the maximum of $L_{AFmax}$ induces some technical difficulties we chose not to measure directly this distance. We cxonsidered that the vehicle will be passing on one of the road lanes and that our geometrical correction $K_D$ will be attached to an uncertainty favourable for the vehicle driver according to its real position on a lane. The following Figure 1 gives an example of the sound level differences and underestimation/overestimation in the $L_{AFmax}$ value when the NR is installed at 8 m of the centre of a lane of 3 m width and at a height of 7 m. According to the reference distance of 7.6 m the maximum error of overestimation would be of 0.9 dB. It means that the $L_{AFmax}$ measured by the sound level meter must be corrected by this first uncertainty.

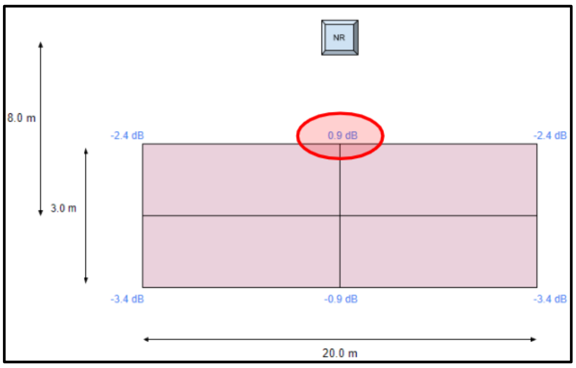


**Figure 1. Example of $K_D$ correction in the monitoring area. The higher value of 0.9 dB would be subtracted from the measured level.**

A second uncertainty is linked to the meteorological condition at the moment of a vehicle pass-by. The correction factors $K_T$ and $K_P$ and used and correspond to:

$$K_T = 15\,log\left(\frac{T_K}{T_{K\_ref}}\right) \qquad (3)$$

$$K_E = -10\,log\left(\frac{p_{atm}}{p_{atm\_ref}}\right) \qquad (4)$$

With $T_K$ the air temperature in Kelvin at the moment of the sound level measurement, $T_{K\_ref}$ the air temperature reference in Kelvin at 23°C, $p_{atm}$ the atmospheric pressure at the moment of sound level measurement and $p_{atm\_ref}$ the atmospheric pressure reference equal to 101325 Pa.

These environmental corrections are inspired from the standard NF EN ISO 3744 [11].

All the other minor uncertainties not necessarily described in this document are included in a correction factor of uncertainty $K_U$. The sound level of the vehicle $L_{veh}$ is then defined considering all the correction factors and uncertainties by:

$$L_{veh} = L_{veh}(D) + K_D + K_T + K_E - K_U \qquad (5)$$

This is the value $L_{veh}$ delivered by the system NR that will be compared with the acceptable pass-by noise value for each category of vehicle. The acceptable pass-by noise levels are defined in the article 3 of the order of May 12th, 2021 [12]. In order to be sufficiently inclusive with all the existing vehicles the maximum value of $L_{veh}$ has been temporarily set to a value of 90 dBA during this experiment. This value will be called the Penalty Threshold (PT) in this document.

## Limitations of the approach

One of the limitations of such devices for automatic control of noise levels produced by vehicles is to make an acoustic camera useful for metrological measurements. In addition, false positives are not accepted in this experiment. This means that no vehicle should receive a penalty by mistake or whose penalty is questionable or doubtful. Therefore, it is clear that:

- The sound pressure level should be performed indisputably with a reference noise measurement. Therefore, the only known reference of IEC 61672 and the use of a sound level meter is needed [6].
- Source contribution engineering measurement methods - such as beamforming or acoustic holography - to obtain the reference level should be outlawed because they can not be done according to a standard, they are non-metrological.
- The use of source localization or noise tracker methods to demonstrate vehicle emergence seems to be useful.
- It is necessary to use detection methods to distinguish road noise from impulse noise, or any type of noise emitted by all near or distant noise sources coming from unmonitored road axes.

## ACOEM APPROACH FOR VEHICLE NOISE DETECTION ACCORDING TO NOISE STANDARDS

The NR system is mostly composed of the following elements:

- A sound locator (ATD-300, brand ACOEM) for intelligent trigger of the overall system and for sound localisation of the maximum of sound pressure level during a pass-by noise event.
- A Class 1 sound level meter (CUBE, ACOEM) for sound pressure measurements of ambient noise.
- A weather station for environmental corrections.
- A 360° video camera for noise identification (projection of the result of the sound locator on the video).
- An automatic number plate recognition (ANPR) camera for plate reading and picture shot for the automatic control.
- A server for overall communication, results computation and publication.

The following Figure 2 shows the ACOEM prototype integrating all these elements.

**Figure 2. ACOEM NR prototype.**

## Intelligent trigger for pass-by noise

In order to limit the information published by the system and to ensure that when the system triggers it corresponds to a vehicle passing in front of the NR, several elements of the soundscape are checked. It is possible thanks to the use of a sound locator coupled with intelligent sound analysis. Several elements are then checked with different weight and corresponds for example to:

- Level L0: exceedance of one sound pressure level other than the Trigger Level (TL).
- Level L1: strong frequency emergence.
- Level L2: emergence extended in frequency and time.
- Level L3: spatialized emergence.

It means that when a mobile source of noise in a specific monitoring area is perceived the system will trigger. The parameters are generally defined between -10 m and +10 m on both sides of the ATD-300 (Figure 3).

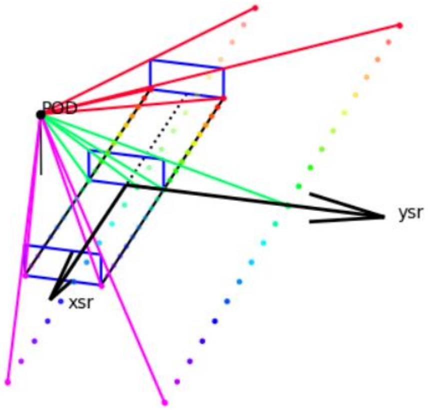


**Figure 3. Example of monitoring area definition.**

A speed range can be estimated from the sound locator and is also configurable. It is usually defined between 10 and 130 km/h. These elements allowed us to make a first filter on the system trigger since no false penalties are authorized within this experiment.

As it is shown in Figure 4 the NR system is able to monitor several lanes (up to 4) that could be not directly parallel to the system.

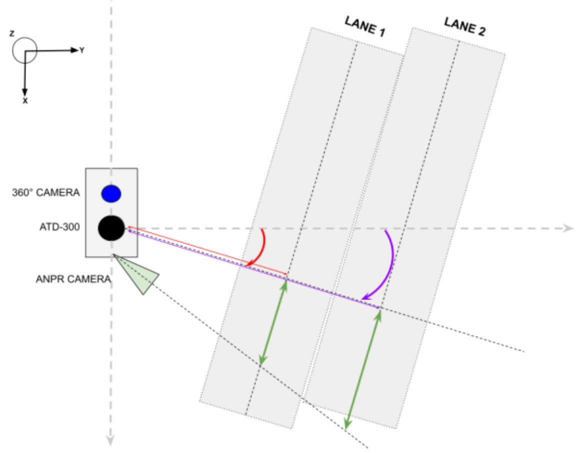


**Figure 4. Example of Lane monitoring for the NR.**

After the trigger validated by the intelligent trigger the server inside the system will retrieve all information of different sub-elements (sound level meters, weather station and cameras) in order to:

- Make a projection of the sound localization of the ATD-300 on the 360° camera.
- Estimate the vehicle speed.
- Automatically detect which lane and direction the vehicle is passing.
- Automatically recognize the vehicle category.
- Perform the sound pressure level correction to compute the $L_{veh}$.
- Automatically compute the moment of the rear image needed for ANPR.

### Example of source tracking

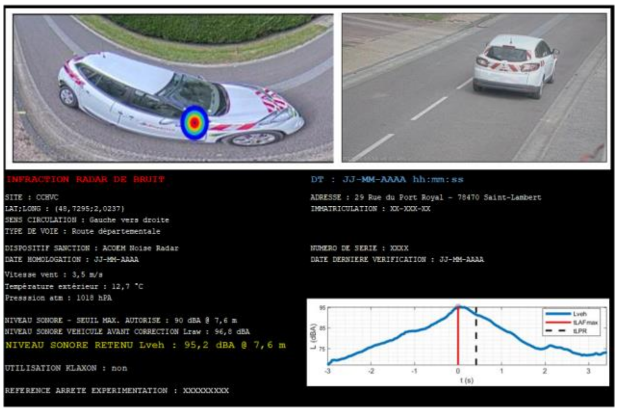
Considering that no false positives are admitted, the tracking is performed by our system realizing a fusion of data between the exploitable information of the different sub-elements. A tracking of the noise source and an image recognition is performed on a certain quantity of images extracted from the video:

- Determining instants equivalent to $t_{LAFmax}$ (time of $L_{AFmax}$)at $t_0$ (-10 m) and $t_1$ (+10 m).
- By identifying the type of vehicle by image recognition.
- By counting the number of image/localization mergers on the different images (image and video overlay) and the total number of vehicles.
- By validating the tracking if there is fusion in the majority of cases.
- By classifying the events by different classes: unambiguous cases and ambiguous cases, as it is the case when more than one vehicle appears on the image. In this case, it is difficorgault to determine metrologically the level of the noise source. A correction has to be applied on the uncertainty $K_U$.

The tracking of the source of noise within the monitoring zone allows us to ensure that inside this zone the same source of noise is predominant. In addition, we actually have the capability to estimate the overestimation on the $L_{veh}$ if more than one vehicle is present at the maximum of $L_{AFmax}$.

### Example of MIF

The following Figure 5 shows an example of a penalty message (from French *Message d'InFraction*).


INFRACTION RADAR DE BRUIT

DT : JJ-MM-AAAA hh:mm:ss

SITE : CCHVC
LAT;LONG : (48,7295;2,0237)
SENS CIRCULATION : Gauche vers droite
TYPE DE VOIE : Route départementale

ADRESSE : 29 Rue du Port Royal - 78470 Saint-Lambert
IMMATRICULATION : XX-XXX-XX

DISPOSITIF SANCTION : ACOEM Noise Radar
DATE HOMOLOGATION : JJ-MM-AAAA

NUMERO DE SERIE : XXXX
DATE DERNIERE VERIFICATION : JJ-MM-AAAA

Vitesse vent : 3,5 m/s
Température extérieur : 12,7 °C
Pression atm : 1018 hPA

NIVEAU SONORE - SEUIL MAX. AUTORISE : 90 dBA @ 7,6 m
NIVEAU SONORE VEHICULE AVANT CORRECTION Lraw : 96,8 dBA
NIVEAU SONORE RETENU Lveh : 95,2 dBA @ 7,6 m

UTILISATION KLAXON : non

REFERENCE ARRETE EXPERIMENTATION : XXXXXXXXX

**Figure 5. Example of MIF for penalty.**

Without explaining all the information in this figure, in the case presented here it is possible to observe that (1) only one vehicle appears on the pictures and that (2) the emergence of this source is more than 20 dB compared to the background or ambient noise (at -1 s before the event and +1 s after the event, this period being still to be defined). It is possible to justify that it is indeed this vehicle which carries the major part of the acoustic energy and that it is distinctly located.

## FIRST RESULTS OF THE NR PROTOTYPE

### Results in a controlled environment

According to the procedure proposed by the CEREMA working group several tests have been carried out on a test track in order to evaluate the different prototypes proposed by the industrials. These tests included:

- Single vehicle tests.
- Successives vehicles tests.
- Tests including a noise source.
- Cross vehicles tests.
- Wet pavement tests.

Different situations have been then evaluated composed of isolated vehicles (cars, motorcycles, trucks), several cars and punctual sources of noise. From the exhaustive list of tests, the ACOEM NR system performed well on most cases studied. The following figure shows an example of the entire result given by our system at this stage of the project. It can be seen that even if two cars are present, the system can point out the loudest one on lane 1. In this picture, only 4 moments are selected to make the visual verification of NR prototype results easier. At the end, the MIF of Figure 5 will be the only information transmitted.

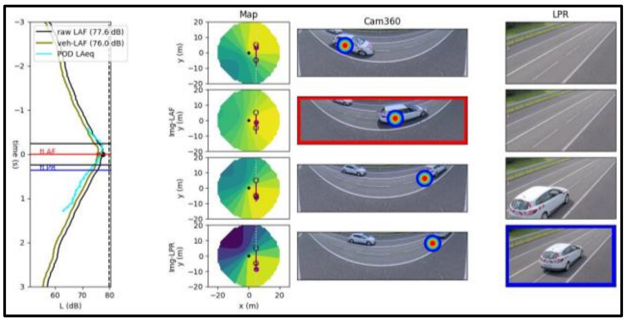


**Figure 6. Example of tracking of the NR prototype.**

- On the left, we can see the $L_{AF}$ measured by the ATD-300 (POD $L_{Aeq}$, informative). It is superimposed to the raw $L_{AF}$ level measured by the Class 1 sound level meter. The $L_{AFveh}$ is also informed and corresponds to the $L_{veh}$. As explained before it corresponds to the $L_{AF}$ level at the reference distance of 7.6 m taking into account distance, weather, environment and uncertainty corrections. The different times pointed out with a line correspond to the time of thed 4 shots (pictures extracted from the video). The red line informs the time $t_{LAF}$ of the $L_{AFmax}$. The blue line indicates the time of $t_{LPR}$ where the picture from the ANPR camera is taken.
- The images under *Map* correspond to an acoustic cartography of noise sources in a horizontal plane with respect to the ground. The solid purple line corresponds to the theoretical trajectory of the noisiest vehicle in relation to the monitored lane (dotted) and the red dots correspond to the exact positions of the emergence source. The Y and X axes are interchanged with respect to previous Figures 3 and 4. Y corresponds well to the path from left (positive values) to right (negative values).
- The pictures under *Cam360* correspond to the spatial visualization of the emergence noise source. In the particular case of a noisy vehicle followed by a non-noisy vehicle, it can be noted that the spatial localization follows the noisiest car. Red image corresponds to the moment of $L_{AFmax}$.
- The images under *LPR* correspond to the images associated with each of the 4 instants of the shot. Blue image will always be the one associated with the shot that will allow the vehicle registration number to be extracted. In the case of a vehicle passing from right to left, it is image 1 that will allow this information to be extracted.

The noise source tracking method showed good results in order to discountWe  difficult cases with several vehicles without one with a high emergence in the sound pressure level. It also showed without surprise that the wet pavement induces an increase in the sound pressure levels. The punctual source of noise showed some limitations of our system giving some overestimations in the $L_{veh}$. However, those overestimated levels can be also due to reflections of the external source of noise on the tracked vehicle, so, how to discriminate in this case the noise of the vehicle from the external noise? We are faced with complex situations that are maybe not representative of NR use cases. On the other hand, at least the conditions for the utilisation of such automatic devices should be fully controlled at the moment of a site choice.

## Results in a non-controlled environment

Since March of 2022 several ACOEM NR prototypes have been installed in 4 sites with different soundscapes:

- Communauté de Commune de la Haute Vallée de la Chevreuse: rural area with low daily traffic.
- Nice: urban area with high daily traffic.
- Rueil-Malmaison: suburban area with very high traffic.
- Toulouse: urban area with high daily traffic.

The system installed showed pretty good results with some limitations due to (1) its environment and the ease of installation (in some cases the radar is not enough away from the different lanes which limit the noise source tracking for example) and (2) to poor control of the synchronization between the different sub-elements. It could give us interesting feedback on possible improvements on the system. It has also been seen that all the possible acoustic situations were not fully investigated before the beginning of the experiment and that new complex soundscapes should be analysed or at least ignored by the system to avoid false penalties.

At least, our system showed us that when an almost isolated vehicle passes in front of the device beyond the PT the system is fully able to detect it and to send a possible penalty.

An analysis of the collected data during at least 3 months of experiment showed us that such systems are extremely powerful in allowing rich information to be extracted from the soundscape: a true infographic of road traffic noise is thus carried out automatically.

To demonstrate the potential of typical analysis at a glance, let us take the example of an urban site with heavy traffic from.
Crossing the "estimated speed" parameters of the vehicle and the acoustic level "Lveh" of each event provides a direct and global view of the noise emissions from road traffic at a site.

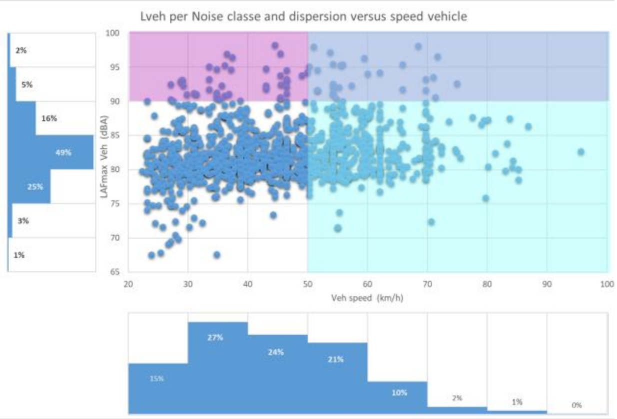


**Figure 7. Correlation between vehicle speed and pass-by noise.**

The analysis of Figure 7 shows that there is no strong correlation between vehicle speed and the noise it emits. Vehicles emitting an Lveh greater than or equal to 90dBA represent 7% of total road traffic at the premises considered.
Speed radar and Noise Radar are in this case complementary. It is important to remember that the vehicle speed estimated by the NR device is only indicative and cannot be used for any purpose other than soundscape contextualization data.

The second example of advanced analysis concerns the same implantation site. This involves comparing the hourly dynamics of the number of vehicles passing between an “average Monday” between the months of March to June and an “average Saturday” over the same period of the year.
The lower graph in Figure 8. represents the hourly percentage of noisy vehicles' pass-by (are considered noisy vehicles, vehicles with an Lveh greater than or equal to 90 dBA).

Unsurprisingly, vehicle traffic on morning hours (5 a.m. and 11 a.m.) is much higher on Monday than on Saturday. From mid-afternoon until late at night, the observations are reversed. No big reveal here: the data reflects the city's dynamic between people who work during the week and come home later on weekends.

On the other hand, the analysis of the ratio of noisy vehicles is much more instructive! Variations in the volume of road traffic do not seem to explain the variations in the share of noisy vehicles. Smoother traffic could have explained the presence of more noisy vehicles. There is also no established time pattern: noisy behaviour is no more present at night-time than during the day. On the other hand, there is a great increase in the percentage of noisy vehicles at the weekend compared to the working day, and those during all hours of the day.

Additional analysis could be done to verify some possible explanations for the observed trend. Is the increase in the rate of noisy vehicles during the weekend related to a higher number of motorcycles in the vehicle fleet? Alternatively, maybe this phenomenon is linked to more uncivil behaviours of drivers during this time of the week?

The objective of this study is not to progress further to answer this question in particular: it is just a question of illustrating the power of the automated statistical analysis that such intelligent multi physical sensors allow.

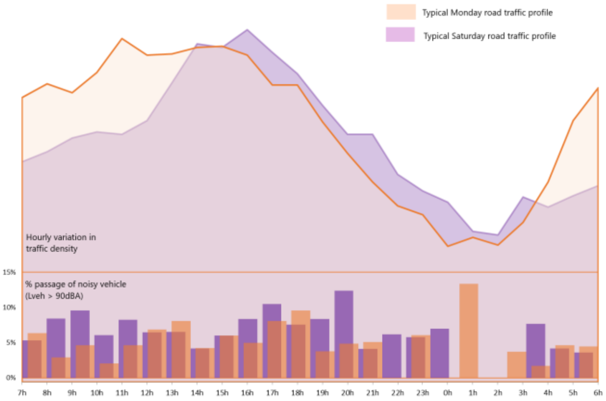


**Figure 8. Comparison of hourly traffic density with associated noisy vehicle ratio.**

## BECAUSE WE CAN ONLY CONTROL WHAT WE UNDERSTAND

Noise observatories, such as ACOUCITÉ in France, guarantee the process of combating noise pollution. Their action usually revolves around three stages.

- UNDERSTAND the phenomenon involved in noise pollution.
- EVALUATE the effectiveness of action plans.
- INFORM and disseminate knowledge.

The smart component Noise Radar sensor allows the characterization of each event making up the noise pollution. Traffic noise, general and obscure, becomes a tangible nuisance because each event, each noise offender, can be individualized: it highlights the noise dynamic on a road axis. In this sense, NR produces data to better "understand" the inconvenience of local residents.

Is the loudest pass-by noise due to a specific vehicle class? Are the noise offenders also speed offenders? Is there a repetitive pattern? On a daily basis, weekly basis or even yearly seasonality?

Drawing up an action plan for the preservation of a place or to recover a degraded environment is now much assertive.

Giving this information through intelligent acoustic sensors (are not only automatic devices for sanction) to better understand the noise annoyance due to traffic noise is also a valuable ally for documenting the benefits in terms of reduction of noise pollution after the implementation of a low emission zone, for instance.

Until loud vehicle penalty is a reality, an important lever remains the public awareness. As NR enables the individualization of each noise event, an intelligent acoustic sensor directing the message in real time to the most important target - the noise polluters - is now an item of the toolbox that the city noise manager's toolkit should have.

NR paves the way for the implementation of educational sound radar fulfilling the double objective: rich measurement for understanding noise pollution and communication with noise offenders for the most effective awareness-raising action.

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