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The development of a new tire-road noise measurement device in France

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ABSTRACT

Traffic noise emission is largely influenced by the road surface properties. These acoustical properties are evaluated by measuring the noise generated by tires rolling on it. Usually this is achieved with static pass-by measurements, but many advantages were found in developing continuous dynamic measurements in the close proximity of a rolling tire. An equipment was designed in France, where three microphones are mounted near the contact zone between the road surface and the tire of a test vehicle. With this equipment, it is possible to evaluate the tire-road noise generated at different speeds ranging from 50 km/h up to 130 km/h, but at a constant pace along a road section.

The development of such a method for the evaluation of road surface properties, requires that the specific effects of the vehicle, the tire and external noise contributions are mitigated and removed if necessary. A great care was paid on the investigation of the aerodynamic noise contribution due to the displacement of the microphones along with the vehicle. Experiments were made indoors, in an airflow produced by a wind turbine, in order to qualify and evaluate the turbulent air flow around the microphones, and design appropriate windshields. Additional experiments performed outdoors on real measurement conditions confirmed that when using standard windshields, the tire-road noise level is more than 10 dB(A) higher than the airflow noise contribution, which makes this later negligible. Further investigations on the possible perturbing sources were made, like the vibration of the mounting system, the influence of the engine noise, the effect of the type or width of measurement tire, and the effect of external noise due to other vehicles in the traffic flow.

RÉSUMÉ

Le bruit du trafic routier est largement influencé par les propriétés des revêtements de chaussée. Ces propriétés acoustiques sont en général évaluées par une mesure statique de bruit de roulement au passage de véhicules. Mais une demande forte s'est exprimée en France pour le développement d'une méthode de mesure en continu du bruit de roulement, permettant d'évaluer les performances acoustique des revêtements de chaussée, aussi bien en milieu urbain que sur le réseau interurbain. Un dispositif de mesure a été développé, dans lequel trois microphones mesurent le bruit à proximité d'un pneumatique d'un véhicule d'essai en roulement. Cinq véhicules ont été instrumentés à l'identique dans 5 laboratoires différents, afin de tester la reproductibilité de la méthode. A l'aide de cet équipement, il est possible de mesurer le bruit généré par le contact pneumatique – chaussée à différentes vitesses entre 50 et 120 km/h, mais par pas de distance constants au long d'une section routière. La longueur de ces segments constants correspond à un nombre entier de tours de roue, que l'on peut adapter à l'objectif de la mesure.

Il est nécessaire que les effets spécifiques du véhicule, du pneumatique ou du bruit extérieur soient maîtrisés et éliminés si nécessaire. Des recherches approfondies ont porté sur la contribution du bruit aérodynamique dû au déplacement du système de mesure avec le véhicule. Des expérimentations en laboratoire à l'aide d'un ventilateur simulant le flux d'air à différentes vitesses d'un véhicule en déplacement, ont permis de qualifier et quantifier le flux turbulent autour des microphones. Différents dispositifs anti-vent ont pu être testés. Des mesures réelles sur le véhicule ont ensuite confirmé que les niveaux de bruit de roulement mesurés avec des protections standards sont supérieurs de plus de 10 dB(A) aux bruits aérodynamiques, ce qui rend ces derniers négligeables. Des recherches complémentaires ont été menées sur les sources perturbatrices potentielles, telles que les vibrations du système de montage, l'influence du bruit moteur, du type et de la largeur du pneumatique, et du bruit extérieur dû aux autres véhicules du trafic.

1- INTRODUCTION

Road traffic noise is a major and growing environmental problem in France and other European countries. Reducing the noise emitted at the source is of a great interest, especially in dense urban areas where the space for noise barriers is limited. Engine and transmission noise have been drastically reduced over the twenty past years, and as a consequence, the tire-road contact is now the main source of noise generation on light vehicles driving above 30 km/h (above 60 to 80 km/h for trucks). In order to reduce this tire-road noise, the improvement of pavement properties is promising, and differences as much as 12 dB(A) have been obtained between noisy and quiet pavements in France. But technological improvements require that evaluation tools are available. The evaluation of noise properties of pavements is useful for classifying the road pavements in terms of noise reduction potential, for assessing the noise reduction of a newly laid pavement, and for monitoring the aging of a road section or network. The current method for evaluating these noise properties is a pass-by measurement method. It will be presented first. Then the continuous dynamic measurement method developed in France will be presented next, with a description of all the investigations performed in order to assess the quality of the method.

2- THE EVALUATION OF NOISE PROPERTIES OF ROAD PAVEMENTS

2.1- Pass-by measurements

The wider used method for measuring tire-road contact noise is the pass-by measurement method, in which the A-weighted maximum sound pressure level L_{Amax} of a passing vehicle is measured by a microphone located in the road near field, 7.50 m from the road axis and 1.20 m above the road surface. Each vehicle run is characterized by L_{Amax} and the vehicle speed measured with a radar. For road surface characterization, this measured noise must be independent of the tire and vehicle characteristics. Thus, a large number of vehicles picked up from a real traffic flow are measured, and a statistical analysis is performed, by calculating a logarithmic regression of the L_{Amax} vs. speed data. With this regression curve, it is possible to define the A-weighted reference sound pressure level at the reference speed, which is, after correction for temperature effects, the reference indicator for acoustic performance of the road pavement. The reference speed depends on the type of vehicles (passenger car or dual or multi axle trucks) and the type of road (highway, main road, local road...). The same procedure can be followed for each third octave frequency band, and a reference noise spectrum usually

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ranging from 100 Hz to 5 kHz can be derived. The measurement procedure, also known as Statistical Pass-By method (SPB) is described in an international standard ISO 11819-1 [1].

This procedure shows an acceptable reliability (less than 1 dB(A) repeatability and 1.5 dB(A) reproducibility). The method is appropriate for the characterization of road noise environment, because it includes all types of vehicles in a real traffic. By use of propagation models, it is possible in some simple cases, to estimate from SPB measurements the equivalent sound pressure levels (L_{eq}) at façade of building - the indicator for legal requirements [2]. This procedure is however a “static” method, the road surface properties are evaluated at a specific spot where the microphone is set. It is not possible to check on non-homogeneity of the pavement. Furthermore, drastic site conditions are required, where no obstacle must be present in the vicinity (no building, no barrier or earth-berm...), no slope, no curve, the surface between the road platform and the microphone position must be flat and homogeneous... These drastic requirements makes it almost impossible to operate in dense urban areas, where noise problems are the most critical.

2.2- Continuous measurements, or close proximity method

Because of these limits, it can be of a great advantage to perform continuous dynamic measurements within a traffic flow. The principle of the method consists in fixing a microphone to a wheel, close to the tire-road contact zone, and to measure the noise continuously while the tire is rolling. The measurement can be performed on the test tire of a trailer, or on the tire of a vehicle. In the case of the trailer, the tire fitted with the measurement equipment is usually covered by an enclosure in order to limit the noise pollution by the surrounding traffic and aerodynamic flow. The difficulty is then to make this enclosure as sound absorbent as possible in order to limit the sound reflections inside the enclosure. In the case of measurements on the tire of a test vehicle, the microphones are likely to be more exposed to aerodynamic and other perturbing noise sources. Many different types of tires can be tested in order to make the method as independent of the tire characteristics as possible, but with the restriction that they must fit to the vehicle or trailer. Consequently, only tires with approximately the same size can be tested. The operating principle consists in collecting a large amount of sample data – i.e. average noise level and speed data on road segments – and to estimate an average noise level at a reference speed by a statistical analysis on these data. This analysis can be a regression or a simple arithmetic average after speed correction. Road segments are typically a few meter long.

2.3- A state of the art on close proximity method

Many such measurement systems exist around the world, most of them being trailers. The agreement between measurements with these devices is an important issue. A standard method is still under discussion at the International Standardization Organization, but a comprehensive description exists in a draft document [3]. A round robin test was organized in 2000 between many CPX devices, but a good agreement could not be proved. In France, a comparison between four existing devices was performed on a motorway section with four different road surfaces. The agreement, although acceptable in terms of classification on global noise performance, was not fully satisfying, especially for the porous road surface where unexplained discrepancies occurred [4]. For this reason, a research project for developing a new method was initiated. This method is intended for the acoustical classification of road surfaces (expert method), the assessment of road surface acoustic performances (check of

conformity of production), and for the monitoring and diagnosis of road surface condition on a network. The method must be valid on short (100 m long) or on long (50 to 100 km) sections, on dense urban roads or on fast inter-urban roads. Five vehicles were identically equipped in five Public Works Laboratories, so that the reproducibility of the method can be estimated.

3- THE MEASURING SYSTEM

3.1- The test vehicle

The measurement device is a self powered vehicle, a passenger car Renault Scénic, only used for acoustic measurements. The reference tire configuration is Michelin Energy XH1 reference 195/60/R15, the mileage of which is approximately 1000 km during the tests presented later in the paper. This is a standard configuration, commonly available on the market. A set of 3 microphones is fitted to the vehicle, near the back right wheel. This position is chosen in order to be as far as possible from the engine - i.e. back wheel - and as far as possible from the exhaust pipe - i.e. right side on this car. Two microphones (#1 and #2) are fixed to the car body, on the side of the tire according to ISO [3] positions, i.e. 0.20 m from the axe of the wheel, and 0.10 m above the road surface (figure 1). They are mounted on streamlined bars made from model aircraft building material. A third microphone (#3) is fixed on the trailer coupling, at the rear of the wheel in the horn. It is positioned at 0.80 m from the axe of the wheel, at 0.15 m above the road surface. This position has been used for many years in France, in the city of Paris especially, where the lateral positions were thought to be too dangerous for pedestrians.

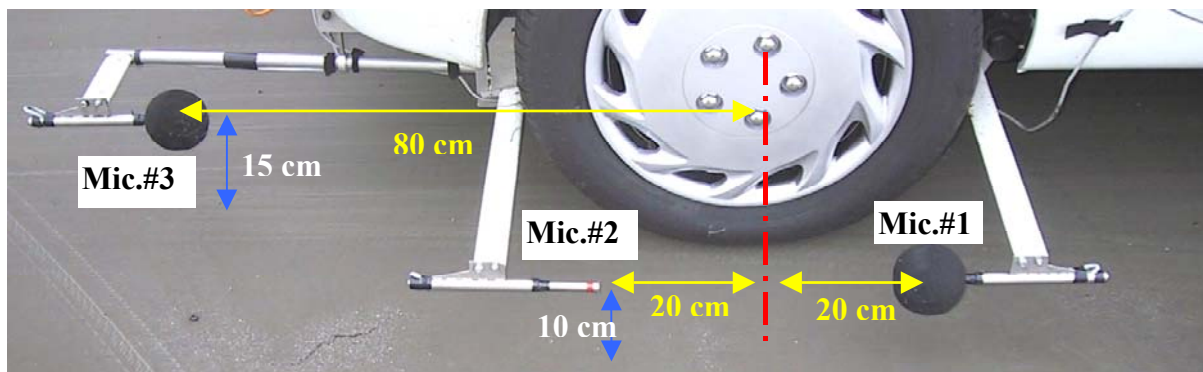


Figure 1. Position of the 3 microphones and mounting systems

3.2 The acoustic data acquisition system

The data are acquired on a 5 channel system : 3 are dedicated to the acoustic signals measured on the 3 microphones, one is for the tachometric information taken from the dashboard, and an additional channel can be used for audio comments from the operator during the measurements. The tachometry delivers an indication of the distance run (and subsequently the speed), and fixes the “period” on which the noise level is integrated. Therefore, instead of being time-averaged, the noise levels measured at each microphone are averaged on constant length segments, the distance of which can be fixed from one to several wheel rotations. In this way, on a complete road section, noise levels are evaluated on segments that can be easily

localized, and that all have the same length whatever the driving speed of the test vehicle. An infra-red sensor located on the car body, starts the acquisition on the 5 channels simultaneously, when a retro-reflecting surface (honeycomb type) it met on the road side. It is possible to measure several times the tire-road noise at different speeds and to evaluate exactly the same road segment. For the acoustic classification of a road material, or the conformity of production, a refined evaluation is needed and short segments can be used (1 or 2 wheel rotation long). For the acoustic monitoring of a large part of a network, larger segments must be considered (10 to 50 wheel rotations for instance). In this paper, measured road segments will be 2 m long (one wheel rotation), and a regression on 8 runs at different speeds will be performed to derive the average noise level at the required speed.

4- QUALITY ASSESSMENT OF THE METHOD

4.1 The effect of vibrations

The vibrations at the microphone locations were measured at different driving speeds of the vehicle. An example is shown in figure 2 for the front bar vibration at 130 km/h. The objective was to optimize the mounting system of the microphone support (eg. fixed on the chassis instead of the car body or wheel axle, pre-strained supporting bar...), and to quantify the vibration levels borne by the microphones. It appears that these vibration levels are quite important at very low frequencies, between 20 and 50 Hz. These frequencies are much lower than tire-road noise frequencies, typically ranging from 100 Hz to 5 kHz. In this range, vibration levels are not exceeding 10 to 20 ms^{-2} at the driving speed 130 km/h. This would generate disturbing noise levels much lower than tire-road noise levels.

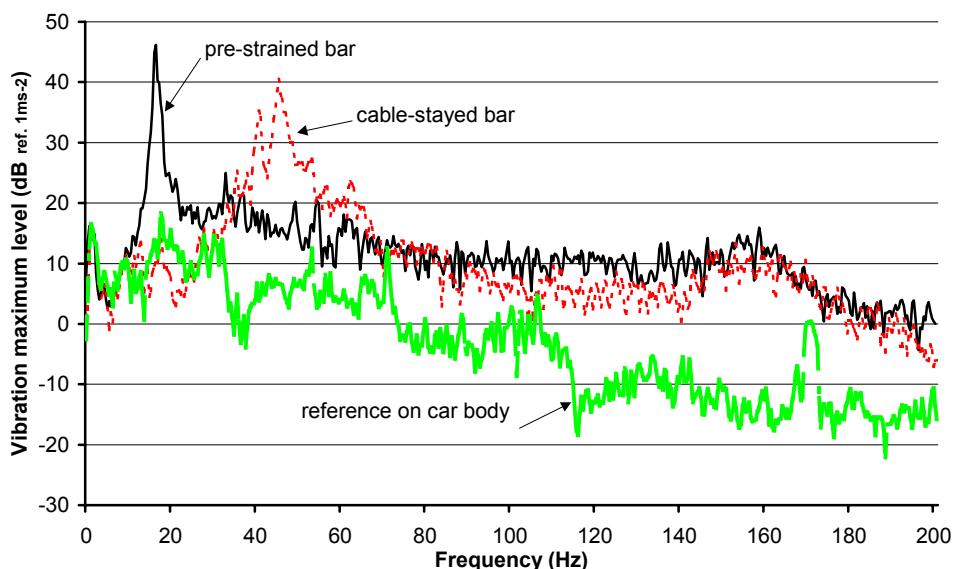


Figure 2. Vibration levels at the front bar (mic.#1) at 130 km/h

4.2- The effect of aerodynamic noise

The main concern with such a mobile system is to get rid of disturbing noise due to the displacement of the measuring system in the air. This produces aerodynamic noise and vibration of the system. The objectives of the research is :

- to analyze the aerodynamic effects in the vicinity of the measuring microphones ;
- to evaluate the temporal and spectral contributions of this noise to the tire-road noise
- to design, if necessary, the relevant mounting and shielding systems

First, a simulation was performed in a test laboratory where a wind turbine produces air flows at different speeds. The turbulent nature of the air flow around the microphone was observed, and the wind speed around the microphone quantified, using Pitot tube sensors. The aerodynamic noise was estimated for different speeds of air flow, and for different sorts of windshields : a standard windshield (round shape), a thin wind and rain shield, a nose cone, a turbulent screen, a streamlined windshield (Figure 3). It is observed that the noise of air flow is rather high, it can reach up to 90 dB(A) at 100 km/h even with a windshield. The nose cone and turbulent screen are less efficient than the standard windshield and the streamlined windshield for reducing the aerodynamic noise.

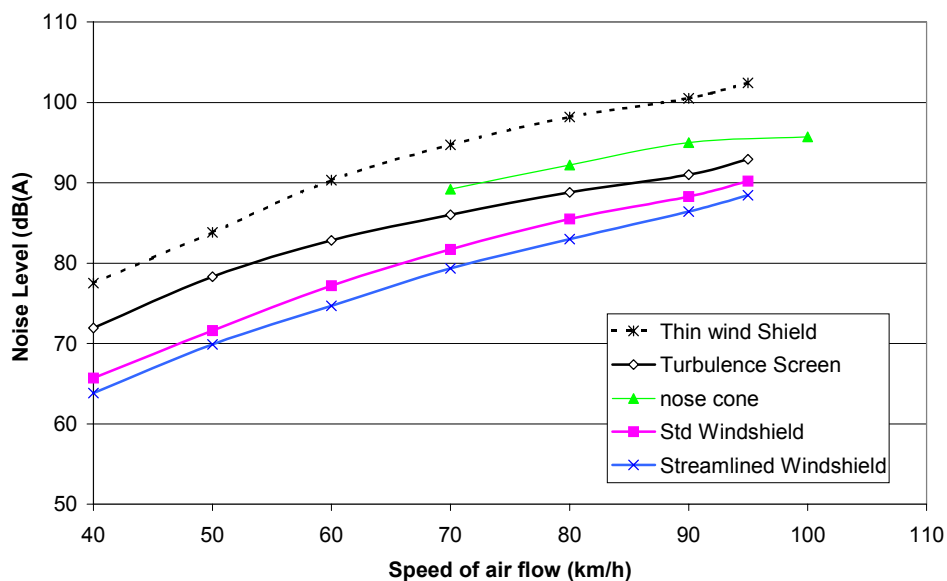


Figure 3. Noise levels relative to the speed of air flow, for different windshields

Furthermore, the actual wind speed in the vicinity of the microphones was measured outdoors on the test vehicle in real driving conditions (figure 4). These measurements confirmed that the speed of air flow on the lateral microphones (#1 and 2) is close to the vehicle speed (figure 5). Of course it is much lower at the rear microphone position (#3) because it is partly protected by the tire and the car body, but this could not be evaluated with such sensors.

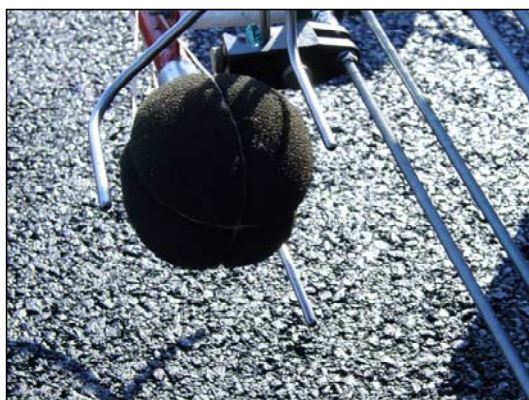


Figure 4. in situ measurements of wind speed (3 pitot tubes) around the microphone

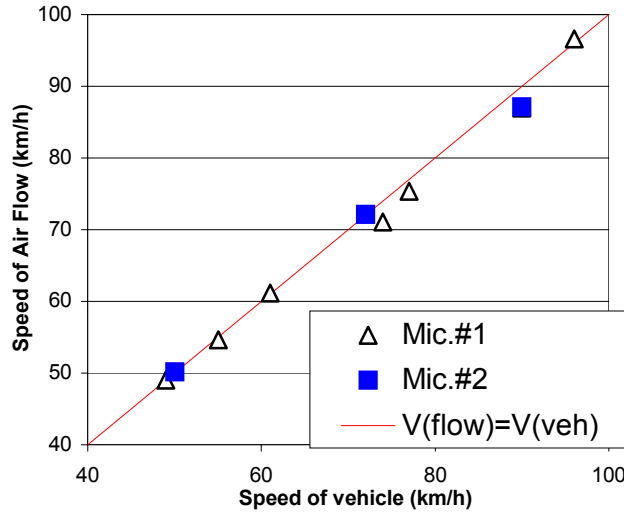


Figure 5. Flow noise vs. vehicle noise

A special streamlined windshield was designed by calculating the optimal “water drop” shape, and smoothing the surface by laser cutting in the foam and covering the external surface with a nylon film. The aerodynamic noise measured in the laboratory with such a protection gave similar (just slightly lower) levels than the standard windshield. In situ tests are currently proceeding. Finally, a chart is drawn, showing the limits of aerodynamic noise in relation to the vehicle speed range (figure 6). The tire-road noise level must be in the upper part or the chart to be air flow noise immune.

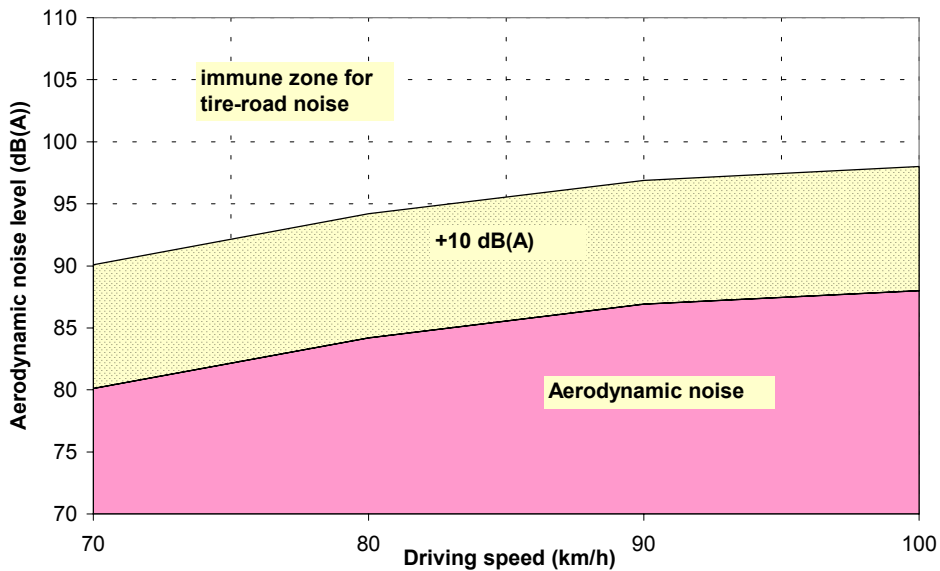


Figure 6. Limit curve for aerodynamic noise disturbance with standard windshield

All these investigations has been made also in the frequency domain. Similar limit curves are available for each third octave band ranging from 400 Hz to 5 kHz, and need to be compared to measured tire-road noise spectra. So far, on the measured road surfaces, the tire-road noise levels were well inside the “immune zone”. That means that the air-flow noise was negligible during the measurements.

4.3 The engine noise and other perturbing sources

It was not possible to measure the tire-road noise with the engine off, because in this case, the tachymetric information is lost and the acoustic acquisition system does not run. The driving condition with the clutch disengaged was however investigated and compared at low speed with the gear engaged at different ratio. The results presented in figure 7 show a very small deviation, lower than 1 dB(A), even at 50 km/h in the 3rd gearbox ratio. Here again, the resulting levels derive from a regression on 8 runs, and an averaging over the 200 m long section of Dense Asphalt Concrete (BBSG 0/10). It can be concluded that the engine noise contribution is negligible even at low speed, when the vehicle is driven at the optimal engine speed (i.e. 4th or 5th gear ratio).

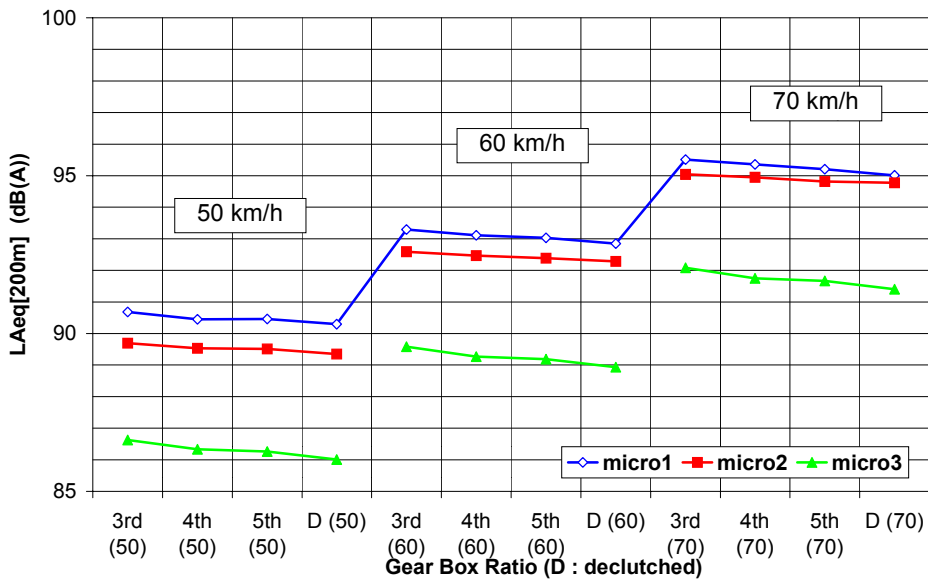


Figure 7. Noise level at the 3 microphones as a function of engine regime

A perturbation was observed on some measurements that could be attributed to exhaust pipe noise radiation. This is particularly noticeable on the microphone #3 located behind the tire. The other two are further and partly screened by the tire. The noise emitted by the engine plus the exhaust system was measured as a function of the engine speed, at the three microphone positions when the vehicle does not move (no tire-road noise). Noise spectra measured at microphone #3 are presented in figure 8 for a few engine speeds. At 4000 rpm, it can reach 85 dB at 125 Hz (engine rotation fundamental frequency), and 400 Hz (exhaust pipe resonance).

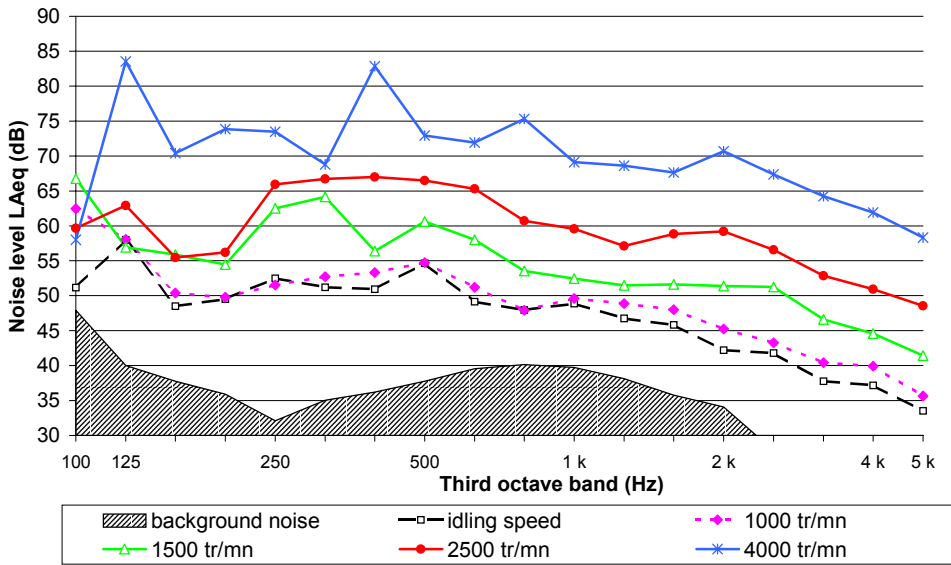


Figure 8. Engine + exhaust noise spectrum at microphone #3

Then, the engine speed as a function of driving speed was recorded in normal driving conditions at optimal gear ratios. Thus, the contribution of engine + exhaust system to the measured tire-road noise level is estimated as a function of the driving speed. This can be resumed in a graph as illustrated in figure 9, where the “immune” zone for tire-road noise is defined, according to the vehicle speed range. For instance, tire-road sound pressure levels above 81 dB(A) when measured at the microphone #3 at a driving speed 85 km/h, are acceptable. Below 81 dB(A), they are contaminated by exhaust or engine noise. As for aerodynamic noise, this comparison should be repeated for each 1/3 octave band. But the analysis of the data obtained, clearly shows that except around the 400 Hz frequency band for microphones #3, the measured tire-road noise levels measured so far are not contaminated by engine and exhaust noise.

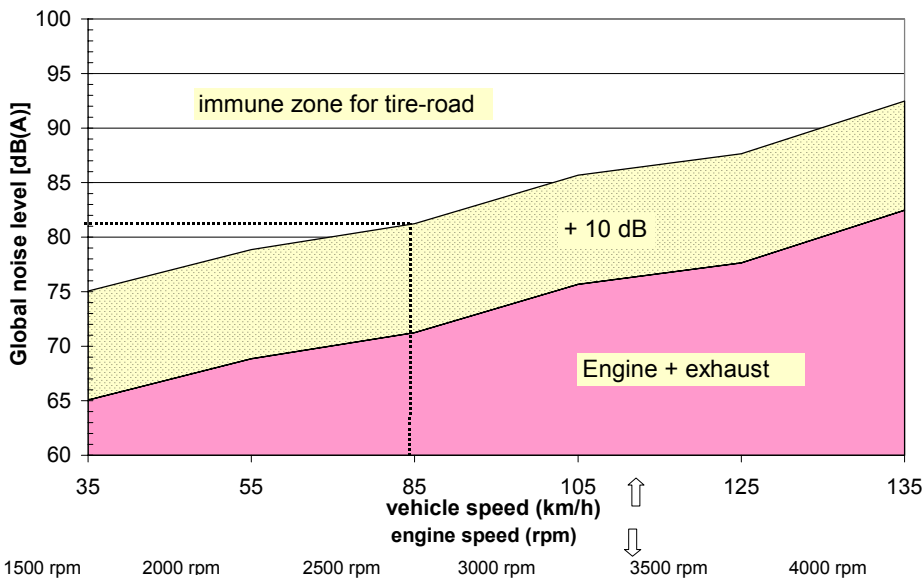


Figure 9. Engine + exhaust noise levels at mic. #3 relative to engine or vehicle speed

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Other potential perturbing noise sources are still under test at present : influence of the other tires on the car, influence of other vehicles in the traffic. These problems will be addressed by simulations. A noise representative of a vehicle passing in the same or opposite direction will be introduced in an uncontaminated measurement, and the effect on the averaging over the length of the measured segment will be estimated. The influence of the other front tire on the measurement, will also be addressed by modeling the sound propagation.

4.4 The influence of the tire characteristics

In the ISO project [2], it is required to perform and average on the noise emitted by 4 different tires, the specific description and composition of which is defined in details in the document. Note that a simple reference tire like a slick tire would not be appropriate because it generates a noise far too peculiar. This strong restriction on the tire characteristics can make the measurements impossible when no tire on the market fulfil (anymore) the requirements. As an alternative, it was decided to use tires commonly available on the market. When they need to be replaced by new tires, a calibration test on a reference road surface will have to be performed in order to adjust the results if necessary. This procedure has been applied successfully over 10 years for controlled pass-by measurements in France. In a first stage, the tests are performed with one reference set of tires defined previously. But many tests were performed to investigate the effect of the size and of the type of tire, on different pavements. The global results in dB(A) at 90 km/h on 5 different sections and for 12 different sets of tires are presented in Table 1. They result from a regression analysis on 8 runs, and are all corrected for a 20°C temperature :

$$L_{Aeq}(20^{\circ}\text{C}) = L_{Amax}(T) + 0.1 (T^{\circ}\text{C} - 20)$$

Road pavement	L_{Aeq} 90 km/h [dB(A)]	Mic.1	Mic.2	Mic.3
Dense Asphalt Concrete (BSG) 0/10 LCPC Test Track	7 tires (new) : 4 makes ; 3 width (185-195-205)			
	<i>Average</i>	98.2	98.0	94.7
	<i>Max deviation</i>	0.8	1.2	1.5
	<i>Standard deviation</i>	0.3	0.4	0.5
Dense Asphalt Concrete (BSG) 0/10 (RN 422)	4 tires : 3 makes ; 3 width (185-195-205)			
	<i>Average</i>	100.6	100.7	98.6
	<i>Max deviation</i>	0.9	1.1	1.4
	<i>Standard deviation</i>	0.4	0.5	0.7
Thin Asphalt Concrete (BBm) 0/10 Lohr Test Track	6 tires : 3 makes ; 3 width (185-195-205)			
	<i>Average</i>	98.2	98.2	96.2
	<i>Max deviation</i>	2.7	1.8	2.3
	<i>Standard deviation</i>	1.0	0.7	0.8
Surface Dressing (ES) 10/14 (RN 422)	6 tires : 3 makes ; 3 width (185-195-205)			
	<i>Average</i>	102.6	102.3	99.6
	<i>Max deviation</i>	0.9	1	1.5
	<i>Standard deviation</i>	0.4	0.4	0.7
Very Thin Asphalt Concrete (BBTM) 0/6 Type 2 (RN 420)	3 tires : 2 makes ; 3 width (185-195-205)			
	<i>Average</i>	96.7	97.8	93.6
	<i>Max deviation</i>	0.4	0.5	1
	<i>Standard deviation</i>	0.2	0.3	0.5

Table 1. Noise levels at 90 km/h with different tires and pavements [LCPC, LRPC Strasbourg]

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The road pavements are ranging from a noisy one (Surface Dressing 0/14) to a rather low noise one (Very Thin Asphalt Concrete 0/6). The results show that the maximum deviation between tested tires is between 0.4 and 2.7 dB(A), and the standard deviation lower than 1 dB(A). It must be specified however the tested tires were common tires, and no selection of noisy or quiet tires was intended. An example in Figure 10 of spectral result for 7 new tires on a Dense Asphalt pavement, shows that no particular frequency effect can be noticed.

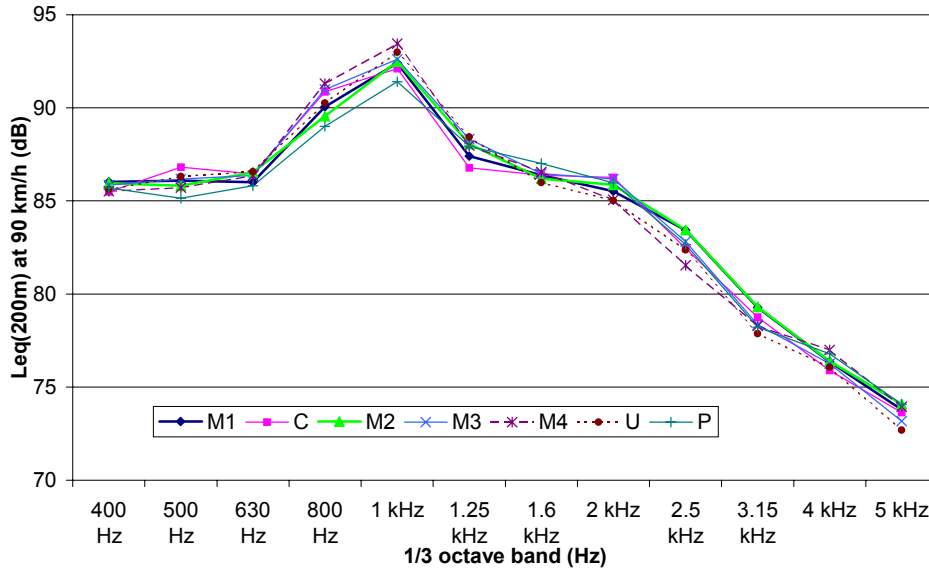


Figure 10. Spectral results for different tires at 90 km/h on a DAC 0/10

5- THE RELATION BETWEEN CLOSE PROXIMITY and PASS-BY METHODS

The obvious question raised when developing a new methodology is “how will it correlated with existing method”, in other words, what is the correlation between close proximity noise levels (CPX) measured on the mobile system, and pass-by noise levels (SPB) ? Actually, the measured sound pressure levels are different, and this difference depends on the type of road surface (porous or non porous) and on the measurement site configuration. Sound pressure levels with CPX measurements are much higher because they are measured much closer to the noise source. The noise source is also not the same : in CPX measurements it is one single tire, but in SPB it is a large number of vehicles. And finally, the propagation path of the sound wave is very different in both cases. In the SPB case, the sound wave interacts with the road environment and may be more or less attenuated when the road surface is porous, or when the shoulder is made of grass.

Some preliminary investigations have been performed first by comparing the CPX noise level with a simultaneous pass-by noise level of the CPX test vehicle. This was performed on a test track on 2 road pavements, one is a Dense Asphalt Concrete, the other a Porous Asphalt Concrete but significantly clogged. The results are presented in Table 2 below.

$\Delta L_{Aeq}[200m]$ 90 km/h (dB(A))	Mic. #1	Mic. #2	Mic. #3
Dense Asphalt Concrete (BBSG) 0/10	21.9	23.2	19.3
Porous Asphalt Concrete (BBDr) 0/10	21.9	24.6	17.1

Table 2. Difference CPX / Pass-By levels of the test vehicle on 200 m sections at 90 km/h

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Another investigation was made on trafficked road, on 4 different sections, but this time comparing SPB statistical level (for passenger cars only) with CPX noise level at 90 km/h. The results are shown in Table 3

ΔL_{Aeq} at 90 km/h (dB(A))	Mic. #1	Mic. #2	Mic. #3
Thin Asphalt Concrete (BBm) 0/10	21.8	22.2	19.9
Surface Dressing (ES) 0/14	20.8	20.9	17.2
Very Thin Asphalt Concrete (BBTm) 0/6 T2	23.8	24.1	20.4
Very Thin Asphalt Concrete (BBTm) 0/8	22.9	23.3	20.0

Table 3. Difference between CPX and SPB noise levels at 90 km/h [LRPC Strasbourg]

The sound pressure level difference between CPX and Pass-By measurements varies between 21 and 25 dB(A) at lateral microphones (#1 and 2), and between 17 and 20 dB(A) at the rear microphone (#3). It seems that pavements having an open porosity give higher differences than dense pavements (except for the porous asphalt, but it is a clogged one, and porosity may be low). It would be interesting to measure this difference on highly porous pavements, especially because noise measurements methods are definitely designed for those quietest pavements.

An approach for modeling the sound propagation between the tire and CPX microphones and between the vehicle and the SPB microphone has been initiated and give consistent predictions with these experimental results [5]. They also predict a higher noise level difference in the case of porous pavements.

6- CONCLUSIONS

In this paper, a new mobile system for measuring tire-road noise is presented. It is intended to be used for the evaluation of road surface noise performances, during a classification scheme, for the assessment of legal requirements, or for diagnostic or monitoring of road surface condition. A lot of investigations were made in order to assess the significance of the measurements, and it was shown that the possible perturbing noise sources are negligible compared with current tire-road noise measured. Although the design of the test device seems quite simple, the measured results are relevant. Repeatability, reproducibility will be checked in a near future, along with a further investigation on the correlation with pass-by measurements.

7- ACKNOWLEDGEMENT

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