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Compilation of some novel approaches for rolling noise evaluation in vehicles

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ABSTRACT

Traditional standardized methodologies for tyre/road noise evaluation are commonly based on sound pressure level measurements (SPL). The Coast-By method (CB) stablishes the measurement point at 7.5m away from the test vehicle path; the Close-Proximity (CPX) is focused on measurements in the close field of the tyre-pavement interaction region; and the Drum method (DR), which is not currently a standardized procedure but is widely used for research purposes, is usually applied for measuring in similar positions to the CPX ones. These methodologies provide their results as an expression of the SPL, but this is not an inherent magnitude to the sound source and hence it may be affected by environment, attenuation or distance. Aimed at assessing the tyre/road noise emission by means of an inherent magnitude, the LIAV-UMH group has focused on designing new measurement procedures that can be used as an alternative to the previous ones. This paper presents these novel approaches, which are partly based on the traditional CB, CPX and DR methods, and also on the ISO 3744 standard, but their novelty lies in providing the sound power level (SWL) emitted by the rolling tyre.

Keywords: Tyre/road noise, Sound power level, Measurement methodology
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1. INTRODUCTION

The exterior noise emission in vehicles is greatly influenced by the driving speed. In that sense, at low driving speeds –below 30km/h– the predominant noise emission comes from the power unit noise, whilst for higher speeds the noise generated at the interaction between tyres and pavement becomes the vehicle's most relevant noise source. The increasing presence of alternative powered vehicles, that is, electric and hybrid electric vehicles, in urban and interurban traffic fleets could contribute to reduce noise pollution thanks to the lack of mechanical engine. However, tyre/road noise still remains in these green vehicles [1], and according to the recent literature about the sound emission of tyres used for electric vehicles [2, 3], it is generally agreed that tyre/road noise from light EVs does not differ from the emission of conventional vehicles. That fact could be perceived as a benefit, since it can be helpful for pedestrians to identify an approaching vehicle, but it could be also seen as a drawback, as it still contributes to the noise pollution in cities. Given this scenario, further research on the characterization of tyre/road noise emission in alternative vehicles is needed, in order to achieve a useful emission for pedestrians' security but also for a proper emission that could contribute to noise reduction in urban environments.

The tyre/road noise emission has been widely studied during the last decades, mainly focused on tyres for conventional vehicles, which provides a deep knowledge about such a noise source and has favoured that evaluation techniques have progressed. In that sense, different assessment methods are collected in the literature, from standardized procedures to specific research methodologies. Among the standardized procedures, the Coast-By (CB) methodology [4] is the current procedure for approval of new tyres to sound emission; the Close-Proximity (CPX) [5] is focused on tyre/road noise assessment from the road surface characteristics point of view; and the microphone locations defined in the CPX method for measurement in the close field of the tyre/road interaction are usually employed for tests bench measurements, according to the Drum (DR) method [6]. Regarding specific methodologies for research purposes, different groups have proposed their own evaluation methods depending on the objective of the measurement, comprising from measurements carried out at the roadside to measurements with microphones boarded on the vehicle test or measurements under controlled laboratory conditions. In [7] there is an extensive revision of the measurement techniques developed during the past years, including from methodologies based on sound pressure level measurements to sound intensity tests or sound field holography analysis.

The Acoustic Engineering and Vibration research group (LIAV) of the Miguel Hernandez University of Elche (UMH), in Spain, is working since the last decade in the development of alternative methodologies [8-11] for tyre road noise assessment. The common aim and the novelty of the new methodologies developed by the group lay on the evaluation of tyre/road noise emission by means of a standardised specific engineering method for determining sound power level. While some research groups have tested tyre noise emission using standardized methods or even drums, most of them provide the results as an expression of the sound pressure level [12], but just a very few assess the sound power emission of the source [13-15]. The advantage of providing tyre/road noise emission as a sound power level magnitude is its invariability, as unlike the sound pressure level, it is independent of other external elements such as environmental conditions, attenuation factors or distance between source and receiver. All the methodologies presented here share to be based on the premises described in the ISO 3744 standard [16], which provides a procedure to obtain the sound power level of a noise source by means of sound pressure measurements, combining the expertise of the ISO method with the experimental procedures developed by the LIAV-UMH research group. This paper summarizes the procedure to obtain sound power levels of a tyre according to three different alternative methods.

2. THE ALTERNATIVE COAST-BY METHODOLOGY

The Alternative Coast-By (A-CB) methodology [17] is designed to assess the sound power level of the noise generated during the interaction of the tyres of a vehicle with the pavement, when it is being driven under Coast-By conditions. In such a situation, the engine is shut off and the transmission is placed in neutral, and the hypothesis that the noise generated by the vehicle is supposed to come exclusively from the tyre/road interaction is assumed. Also the hypothesis that each tyre is an omnidirectional point source moving over a reflecting plane is taken into account.

The methodology is based on the procedure described in the Directive 2001/43/EC [18] and on the ISO 3744: a vehicle test, that is equipped with the tyres under evaluation, approaches the test area at a constant speed; when it reaches the test area, the motor is shut off and the transmission is placed in neutral, until the vehicle passes the entire test area by its own inertia. The procedure is repeated at least five times per each test speed.

A cloud of microphones are located at the centre of the test area, see Figure 1, strategically placed, conforming an imaginary hemispheric surface, see Table 1.

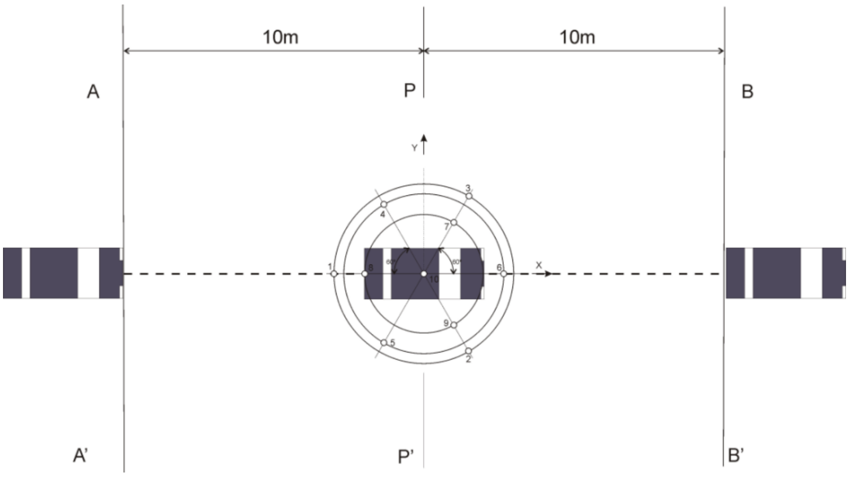

Figure 1. A-CB test area configuration and microphones location.

Table 1. A-CB test microphone locations.

Microphone location	1	2	3	4	5	6	7	8	9	10
x/r_{A-CB}	-0.99	0.50	0.50	-0.45	-0.45	0.89	0.33	-0.66	0.33	0
y/r_{A-CB}	0	-0.86	0.86	0.77	-0.77	0	0.57	0	-0.57	0
z/r_{A-CB}	0.15	0.15	0.15	0.45	0.45	0.45	0.75	0.75	0.75	1.0

The radius of the measurement surface must satisfy the condition:

$$r_{A-CB} > 2 \cdot d_{0\_A-CB} \tag{1}$$

Where:

$$d_{0\,A-CB} = \sqrt{(l_1/2)^2 + (l_2/2)^2 + l_3^2} \tag{2}$$

being l_1, l_2 and l_3 the dimensions of an imaginary reference box that packs up the tyres of the vehicle test: distance between tyres, vehicle width and tyre height, respectively; see Figure 2.

Figure 2. Reference box for the A-CB measurement radius configuration.

The test result can provide the overall sound power level, as well as third octave band levels in the 100Hz to 10kHz frequency range, by means of sound pressure measurements at the indicated positions. The microphone locations comply with far field requirements for the frequency range of interest, according to the ISO 12001 standard [19].

The microphones record the sound pressure levels during each passing-by of the vehicle. The registered data is processed to calculate the average sound pressure level at the split-second when the vehicle is located at the centre of the measurement microphones cloud, according to Equation (3). The location and speed of the vehicle during the test must be accurately known, and for that purpose the use of a global positioning system and photoelectric sensors placed at the ground level are recommended.

$$\overline{L'_p} = 10 \cdot \log\left[\frac{1}{10} \cdot \sum_{i=1}^{N} 10^{0.1 \cdot L'_{pi}}\right] \qquad dB \tag{3}$$

Where $\overline{L'_p}$ is the sound pressure level averaged over the measurement surface in each frequency band, in dB. L'_{pi} is the sound pressure level measured in each frequency band at the *i*th position, in dB.

Environmental conditions and background noise must be controlled during the test. The ISO 3744 provides a procedure to determine a background noise correction factor, *K*, and in such a case, the surface sound pressure level is calculated according to Equation (4). However, it is recommended that the sound pressure levels of interest are 15dB higher than background noise levels, in order to not applying any correction.

$$\overline{L_{pf}} = \overline{L'_p} - K \qquad dB \tag{4}$$

The sound power level of the vehicle's rolling noise from each pass-by is calculated according to Equation (5):

$$L_{W\_A-CB} = \overline{L_{pf}} + 10 \cdot log(S_{A-CB}/S_0) \quad dB \tag{5}$$

Where S_{A-CB} is the area of the imaginary measurement surface according to $S_{A-CB} = 2\pi r_{A-CB}{}^2$ in m^2, and S_0=1 m^2.

3. THE ALTERNATIVE CLOSE-PROXIMITY METHODOLOGY

The Alternative Close-Proximity (A-CPX) methodology [20] is based on the procedures described in the ISO 11819-2 standard [5] and in the ISO 3744, and is designed to assess the sound power level of the noise generated by a rolling tyre installed on a driven test vehicle by means of sound pressure level measurements. Since in the traditional CPX test the microphones are located in the close field of the tyre/road interaction, the measurement positions in the proposed test are located in the far field of the tyre. Then, the hypothesis that the tested tyre is a static, omnidirectional, point source located on two reflecting planes – the road and the vehicle body – is assumed.

The microphones in the A-CPX procedure are located following a quarter of sphere shape, see Table 2. The Figure 3 shows the microphones configuration for a radius of 1 m.

Table 2. A-CPX test microphone positions.

Microphone position	*A-CPX Front down*	*A-CPX Rear down*	*A-CPX Middle*	*A-CPX Front top*	*A-CPX Rear top*
$x/r_{A\text{-}CPX}$	0.86	-0.86	0	0.57	-0.57
$y/r_{A\text{-}CPX}$	0.50	0.50	0.89	0.33	0.33
$z/r_{A\text{-}CPX}$	0.15	0.15	0.45	0.75	0.75

The radius of the quarter of sphere shape must satisfy the condition (6) and it is recommended to be at least 1m.

$$r_{A-CPX} > 2 \cdot d_{0\_A-CPX} \tag{6}$$

Where:

$$d_{0\,A-CPX} = \sqrt{(l_1/2)^2 + l_2^2 + l_3^2} \tag{7}$$

being l_1, l_2 and l_3 the dimensions of an imaginary reference box that packs up the tyre under study, see Figure 4.

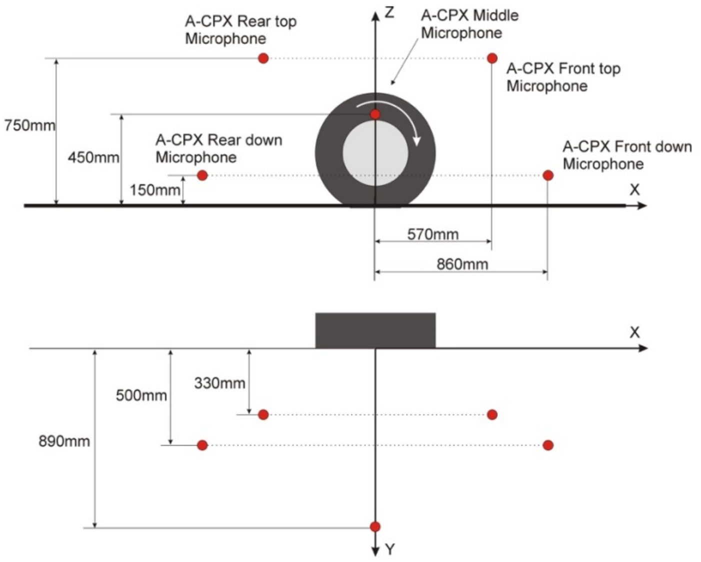

Figure 3. A-CPX microphones configuration.

Figure 4. Reference box for the A-CPX measurement radius configuration.

The test tyre should not be installed on a drive nor steering axle, and the microphones are recommended to be installed by means of slender supporting structures in order to avoid air turbulences that may influence measurements. The data acquisition system, to which microphones are connected, will be boarded on the vehicle. Once the vehicle has reached the test speed, a distance of 200 m must be covered while the microphones record the sound pressure levels generated at the tyre/road interaction. The procedure should be repeated at least 3 times per each test speed. Vehicle speed and environmental conditions should be controlled during the test.

The equivalent sound pressure level registered by each microphone, at every 20m segments into which a 200m road section is divided, are calculated according to (8).

$$\overline{L_{pi,s\,A-CPX}} = 10 \cdot \log\left[\frac{1}{N} \cdot \sum_{i=1}^{N} 10^{0.1 \cdot L_{pj\,A-CPX}}\right] \qquad dB \tag{8}$$

Where $\overline{L_{pi,s\,A-CPX}}$ is the average sound pressure level for the ith microphone calculated for the sth segment, and in each third octave frequency band, in dB. N is the number of samples of the segment, and $\overline{L_{pj\,A-CPX}}$ is the sound pressure level for the jth sample within the segment s, exponentially averaged, in each third octave frequency band, in dB.

The following step is to calculate, per each microphone and according to (9), the averaged sound pressure level for all segments included within each 200m road section.

$$\overline{L_{pi,Section\,A-CPX}} = \frac{1}{10} \cdot \sum_{s=1}^{10} \overline{L_{pi,s\,A-CPX}} \qquad dB \tag{9}$$

Where $\overline{L_{pi,Section\,A-CPX}}$ is the averaged sound pressure level, registered by the ith microphone in the whole *Section*, per each third octave frequency band, in dB.

The averaging of the n repetitions (a minimum of 3, as indicated before) is processed in a similar way, according to (10).

$$\overline{L_{pi\,A-CPX}} = \frac{1}{n} \cdot \sum_{Section=1}^{n} \overline{L_{pi,Section\,A-CPX}} \qquad dB \tag{10}$$

Then, the averaged sound pressure level over the measurement surface is obtained, according to (11). And the tyre rolling sound power level is calculated according to (12).

$$\overline{L_{p\,A-CPX}} = 10 \cdot log\left[\frac{5}{1} \cdot \sum_{i=1}^{5} 10^{0.1 \cdot \overline{L_{pi\,A-CPX}}}\right] \qquad dB \tag{11}$$

$$L_{W\,A-CPX} = \overline{L_{p\,A-CPX}} + 10 \cdot log(S_{A-CPX}/S_0) \qquad dB \tag{12}$$

Where S_{A-CPX} is the area of the imaginary measurement surface according to $S_{A-CPX} = \pi \cdot r_{A-CPX}^{2}$ in m^2, and S_0=1 m^2.

4. THE ALTERNATIVE DRUM METHODOLOGY

The Alternative Drum (A-DR) methodology [21] is designed to assess the sound power level of the noise generated during the interaction of a tyre when rolling against a Drum. This methodology, based on drum tests and the International Standard ISO 3744 determines sound power level of a tyre using sound pressure in an essential free field over a reflecting plane.

The LIAV-UMH drum tyre test facility comprises a Ø1700 mm drum driven by a 110 kW electric motor. Tyres are mounted on slightly modified commercial rims, which are bolted to the test shaft which spins freely around its position. The tyre-rim-shaft assembly is pushed against the drum by means of a hydraulic cylinder. Both ceiling and walls of the test room are made of sound absorbing materials. The dimensions of the test room are 3920x9350x4840 mm.

Measuring instruments such as the tachometer, the load cell, microphones, the pressure gauge or the thermometer, are metrologically inspected and calibrated regularly by external laboratories. Furthermore, the whole laboratory facilities and its activities are audited every year and are accredited by an International Accreditation Body as complying with the standards ISO/IEC 17020 [22] for inspection bodies and ISO/IEC 17025 [23] for test laboratories since 2011. For a detailed list and characteristics of the instrumentation used in the tests, please refer to [21].

The first step in locating the microphone positions is to define a hypothetical reference box which contains the noise source, see Figure 5. The characteristic source dimension $d_{0\_A\text{-}DR}$ is calculated according to (13):

$$d_{0\,A-DR} = \sqrt{(L_1/2)^2 + (L_2/2)^2 + L_3^2} \tag{13}$$

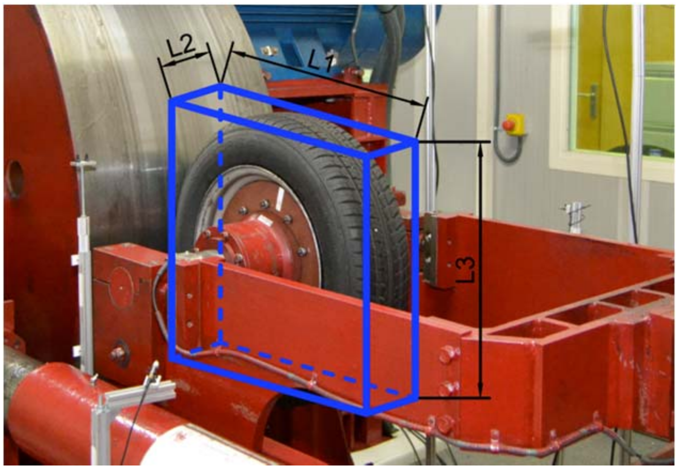

Figure 5. Reference box for the A-DR measurement radius configuration.

The microphones are then placed on a hemispherical measurement surface that has to be centred in the middle of the reference box. The radius $r_{A\text{-}DR}$ of the hemisphere should fulfil the following condition:

$$r_{A-DR} > 2 \cdot d_{0\_A-DR} \tag{14}$$

As prescribed by the standard ISO 3744, microphones are distributed according to the coordinates shown in Table 3 and the microphone array on the hemisphere shown in Figure 6. The microphones are placed by means of different microphone stands made of aluminium Bosch profiles. The stands are placed around the tyre as seen in Figure 7.

Table 3. A-DR test microphone locations.

Microphone location	*1*	2	3	4	5	6	*7*	8	9	*10*
$x/r_{A\text{-}DR}$	-0.99	0.50	0.50	-0.45	-0.45	0.89	0.33	-0.66	0.33	0
$y/r_{A\text{-}DR}$	0	-0.86	0.86	0.77	-0.77	0	0.57	0	-0.57	0
$z/r_{A\text{-}DR}$	0.15	0.15	0.15	0.45	0.45	0.45	0.75	0.75	0.75	1.0

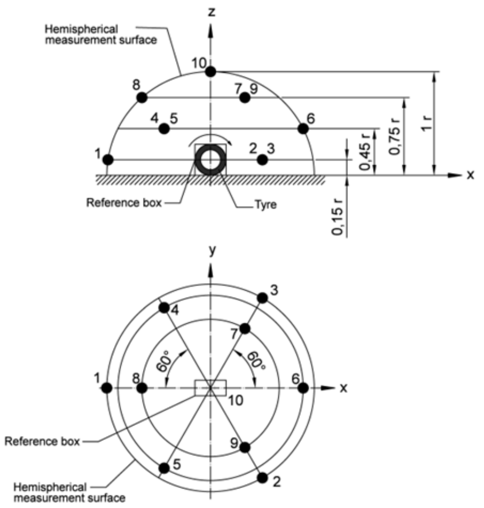

Figure 6. A-DR microphones configuration.

Figure 7. Microphone stands and microphone array around the tyre for an A-DR test.

Correction factors due to background noise K_1 and due to the acoustic test environment K_2 are obtained as prescribed by ISO 3744. Test results for both K_1 and K_2 performed at the LIAV-UMH drum show that the criteria of suitability for background noise and test environment are widely achieved.

As the test room is air conditioned, the temperature was set to 25 ºC while the registered temperature was kept between 24.2 and 24.9 ºC. The LMS Scadas Mobile acquisition system used for the tests, record signals of 5 s between 100 Hz and 10 kHz. All these data is processed in third-octave bands.

Finally, the sound power level $L_{W\_A\text{-}DR}$ can be calculated with equation (15):

$$L_{W\_A-DR} = \overline{L_{pf}} + 10 \cdot log(S_{A-DR}/S_0) \quad dB \tag{15}$$

Where $S_{A\text{-}DR}$ is the area of the imaginary measurement surface according to $S_{A-DR} = 2\pi r_{A-DR}{}^2$ in m^2, and S_0=1 m^2. Please note that $L_{W\_A\text{-}DR}$ is exactly the same expression as equation (5) and that the average sound pressure level $\overline{L_p'}$ is, as well, obtained by means of equation (3). Therefore, the only difference is the way of obtaining the surface sound pressure level $\overline{L_{pf}}$, which is obtained by correcting $\overline{L_p^{'}}$ using the background noise and the test environment corrections K_1 and K_2 as can be seen in the equation (16):

$$\overline{L_{pf}} = \overline{L'_p} - K_1 - K_2 \qquad dB \tag{16}$$

5. DISCUSSION AND CONCLUSIONS

The presented methodologies, A-CB, A-CPX and A-DR, have been designed to evaluate the sound power level of rolling tyres by means of sound pressure levels, under specific and different rolling conditions. All they are based on the fundamentals of the ISO 3744 standard, and according to it, the hypothesis that the noise source is located over one (A-CB and A-DR) or two (A-CPX) reflecting planes is assumed. The microphones distribution around the test tyre follows a hemispherical (A-CB and A-DR) or quarter of sphere (A-CPX) shape, and according to such a distribution, the hypothesis of far field measurements is taken into account.

Different test campaigns were carried out during the development work of these methodologies. The A-CB and A-CPX were tested with Pirelli 175/70R13 82T tyres, installed on a 1991 3-door 1.6 Ford Escort vehicle, driven on dense asphalt, at different reference speeds from 40 to 90km/h. The A-DR was tested in the LIAV-UMH drum facility with four different tyres of two different sizes (185/65R15 88H and 205/55R16 91V): two retreaded Insa Turbo tyres with opposite specifications (eco vs. sport), a standard quality Nexxen tyre and a premium Michelin tyre, at speeds varying from to 40 to 120km/h. The Table 4 and Figure 8 summarize the sound power levels, with A-weighting (dB(A)), obtained at the different tests, expressed in a logarithmic form as a function of the speed *v* and defined by two coefficients *A* and *B*, according to equation (17).

$$L_W = A + B \cdot log(v) \tag{17}$$

Table 4. Sound power levels obtained in the test campaigns, obtained according to the LIAV-UMH novel methodologies.

Method	Tested tyre		L_W (dB(A))
A-CB	Pirelli 175/70R13 82T		$L_{W\_A-CB} = 21.4 + 41.7 \cdot log(v)$
A-CPX	Pirelli 175/70R13 82T		$L_{W\_A-CPX} = 17.0 + 41.9 \cdot log(v)$
A-DR	Retreaded Insa Turbo (Eco)	185/65R15 88H	$L_{W\_A-DR} = 28.5 + 37.9 \cdot log(v)$
	Retreaded Insa Turbo (Sport)		$L_{W\_A-DR} = 19.3 + 41.2 \cdot log(v)$
	Nexxen C. Premier CP461		$L_{W\_A-DR} = 31.7 + 33.9 \cdot log(v)$
	Michelin Enery Saver		$L_{W\_A-DR} = 20.4 + 40.8 \cdot log(v)$
	Retreaded Insa Turbo (Eco)	205/55R16 91V	$L_{W\_A-DR} = 21.7 + 41.3 \cdot log(v)$
	Retreaded Insa Turbo (Sport)		$L_{W\_A-DR} = 8.2 + 47.7 \cdot log(v)$
	Nexxen C. Premier CP461		$L_{W\_A-DR} = 5.3 + 47.6 \cdot log(v)$
	Michelin Enery Saver		$L_{W\_A-DR} = 15.2 + 42.9 \cdot log(v)$

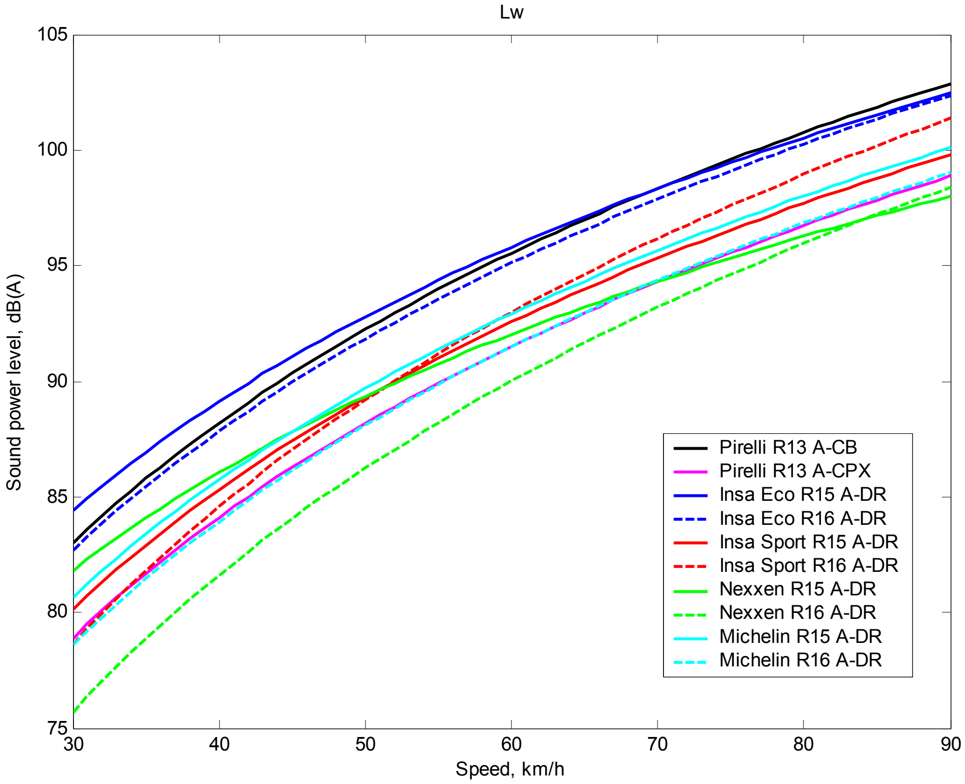

Figure 8. Sound power levels as a logarithmic function of speed, for different tyres, obtained according to the LIAV-UMH novel methodologies.

From different studies in the literature it can be derived that both terms, *A* and *B*, adopt positive values in a range about a few tens. For instance, in [24] a summary of the *A* and *B* terms from different tyre/road noise studies is collected, and the relation between both coefficients is analysed. As it can be observed from Table 4, the *A* and *B* terms are consistent with the values derived from the literature. This fact confirms the viability of the novel methodologies for the assessment of tyre/road noise by means of sound power levels L_W and that these values are similar to the results obtained by other research groups in drum facilities or by means of the CB, CPX, SPB or CPB standard methods as well as to the Normalized traffic noise spectrum according to EN 1793-3 [25] as explained in [21].

Regarding the A-CB and A-CPX methods, in Figure 8 it is observed that $L_{W\_A\text{-}CB}$ is higher than $L_{W\_A\text{-}CPX}$ for the same tyre, due that in the A-CPX test the sound emission is generated by just one tyre, whilst in the A-CB test the emission comes from four tyres. In the A-CB test, the vehicle is in free-rolling, that is, in non-powered operation, and in the A-CPX test the tyre is installed on a dead axle. That fact entails that the rolling of the tested tyre in an A-CPX test could be compared to the conditions in which tyres are running during an A-CB test. Given this remark, a relevant conclusion is that the sound power level emitted by the whole tyres in a vehicle running in coast-by conditions can be derived from the sound power level of a single tyre running in A-CPX conditions, by a logarithmic sum of four equal tyres. In [20] the calculation of the sound power level emitted by the whole set of tyres of a vehicle running in coast-by conditions by means of the logarithmic sum of four tyres previously evaluated by the A-CPX method is shown. The strong similarity between the $L_{W\_A\text{-}CB}$ and the L_W of the sum of four tyres evaluated by the A-CPX method implies that the A-CPX methodology is feasible for assessing the sound power level emitted by the tyres of a vehicle running in coast-by conditions.

Regarding the A-DR method, once the characterization of the tyre test facility was carried out, it was verified that both the limitations for background noise and for acoustic test environment established in ISO 3744 were achieved. Therefore, the acoustic test environment in which the tests were carried out, exceeds the standards of ISO 3744 which guarantees that the obtained results will present a typical deviation of reproducibility for the sound power level equal or lower than 1.5 dB(A) [16]. Additionally, in [21] the sound pressure levels that would be registered at a distance of 7.5 m from a vehicle equipped with the tyre tested on the Drum, have been calculated by means of using a sound propagation model. In the paper it is shown that the difference between calculated sound pressure values and the measured sound pressure values in Coast-By track tests is similar, or even lower than the variability that occurs in the CB track tests due to factors such as the vehicle or the variation of the test surface itself. Besides, results show that the differences in the values registered in the CB track tests between different tyres are analogous to those obtained in the Drum tests between these same tyres, which demonstrate the validity of the A-DR test methodology.

The novel methods presented in the current paper are based in the International Standard ISO 3744 in order to improve the results obtained by the method described in Regulation 117 or by other conventional methods. Hence, the test methods proposed in this paper are not meant to be an equivalent test to the conventional track tests, but they have been developed to become more accurate, alternative tests. In addition, with these methods both the whole noise spectrum and the value of equivalent sound power level can be obtained.

The future step on this research line at the LIAV-UMH group is focused towards the development of a simplified method, based on a correlation among the presented methodologies and reducing the number of measurement points, which could provide an expression of tyre sound emission and could define a standardized procedure for tire noise labelling.

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