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An alternative Drum test method to UNECE Regulation 117 for measuring tyre/road noise under laboratory controlled conditions

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A B S T R A C T

Tyre/road sound emissions have been proved to be the main source of noise caused by road traffic when traveling at medium and high speeds (Sandberg and Ejsmont, 2002). Tyre/road noise has been widely studied among the last decades. However, an important part of this research has been focused, mainly, on track tests. Different track or road methods have been developed for measurement of tyre/road sound emissions. The most important ones are the Coast-By, the Close-Proximity, the Statistical Pass-By or the Controlled Pass-By methods. Among all of them, the Coast-By method has been raised in Europe as standard method concerning the approval of tyres with regard to tyre/road sound emissions as preconized in UNECE Regulation 117 (2007)[2]. However, all the above mentioned methods have several disadvantages such as the influence of environmental factors, the different results that can be obtained depending on the test track or the vehicle upon which the tests are carried out, the lack of repeatability or, the most important aspect, which is the limitation of the measured magnitude, the sound pressure level.

A new methodology (Clar-Garcia et al., 2016) based on drum tests and the ISO 3744 (1994), which was developed in order to avoid these limitations, has been proved to be comparable to the Coast-By (CB) method. This paper describes how different tyres have been tested according to both the CB and the new Alternative Drum test method (A-DR) while their results have been compared. In order to be able to carry out this comparison, as the measured magnitudes and test conditions differ widely from one test to another, the standardised ISO 9613 sound propagation method (ISO 9613-2, 1996) has been applied to obtain the sound pressure value at 7.5 m from the sound power level of a tyre measured under laboratory-controlled conditions when rolling against a drum. Results have shown that both methods are not only comparable but also have remarkably similar sound spectra and, for that reason, the new methodology based on drum tests can be used in order to obtain tyre/road noise emission approved values.

1. Introduction

When a car travels at medium and high speeds, the main source of noise is the tyre/road interaction. Additional noise sources like wind turbulence, the engine or the vehicle's transmission have little contribution in the overall vehicle noise over 30 km/h. [1]. This feature is much more important in electric vehicles where lower power unit noise makes this behaviour occur even at speeds under 30 km/h. For that reason, it is important to focus on tyre/road noise reduction in order to diminish road traffic noise emission.

With this aim, the European Union developed UNECE Regulation 117 [2] in 2007 and Regulations 661 [6] and 1222 [7] in 2009. The first one describes the method to measure tyre/road sound emissions for tyres while Regulations 661 and 1222 establish minimum requirements for the external rolling noise of tyres to be sold after 1st November 2012 under CE marking type approval and a classification of tyres according to their noise emission values respectively.

The Coast-By (CB) method, along with the Close-Proximity (CPX), the Statistical Pass-By (SPB) or the Controlled Past-By (CPB) methods have been considered in the standardisation work. Among all of them, the CB method described in Regulation 117, is the only valid test procedure to obtain tyre/road noise emission approved values in the European Union. However, all these methods have several disadvantages and limitations.

First of all, it is assumed that there will be no difference in the sound pressure level recorded when a set of tyres is tested on different vehicles, which is not entirely true. It has been proved that it is not possible to easily reproduce the results when the tests are

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carried out by different test teams on different test tracks [8] and with different vehicles [9]. It is even difficult to achieve the same results in the tests performed by the same team on the same test track and the same vehicle, as there are many other factors that influence the results.

In addition, and despite the use of temperature correction factors, there are other variables such as wind speed and direction, background noise or changes over time [10] (i.e. in the tyres, the test track or in the vehicle itself due to wear and tear) which are not easily weighted. Additionally, differences in reference speeds, vehicle categories and effects of age and surface roughness of the test track may also bring significant discrepancies in the final results [11,12].

Some of the referenced studies [13] indicate that the variation of any of these factors may imply a difference in the recorded values of up to 2 dB. If we add the possibility of varying more than one parameter simultaneously, it can be said that the current method has certain limitations to achieve the repeatability and reproducibility required to a scientific method. It is unacceptable that a tyre rejected by a laboratory due to an excess of 1 or 2 dB could obtain the homologation certificate when tested in another laboratory due to the limitations of the test method.

A new Alternative Drum methodology (A-DR) based on drum tests and the International Standard ISO 3744 [4] was developed to avoid these limitations. The ISO 3744 determines sound power levels of noise sources using sound pressure in an essential free field over a reflecting plane. This new approach combines the expertise of the ISO method with the experimental procedure developed at the research group's drum tyre test facilities.

Several research groups have tested tyre noise emission using drums previously [13]. However, none of them have applied a standardised specific engineering method for determining sound power level. Unlike, all the previous tests have considered sound pressure.

This paper explains how different tyres have been tested according to both the CB and the new drum test method while their results have been compared. It also describes how the standardised ISO 9613 sound propagation method [5] has been applied to make the comparison, as the measured magnitudes and test conditions differ widely from one test to another. Finally it shows and comments on the test results and ends with the final conclusions.

2. Methodology

2.1. Coast-By method track tests

This section explains the configuration and the conditions of the tests carried out for the measurement of the tyre/road noise of different tyres using the Coast-By method described in Regulation 117.

2.1.1. Test configuration and test vehicles

The track test method, defined in Regulation 117, provides the sound level of a set of tyres mounted on a test vehicle rolling on a specified road surface test track. The maximum sound pressure level is recorded by two microphones (P-P') at a distance of 7.5 m on both sides of the track reference line CC' and 1.2 m above the ground, when the test vehicle is coasting at a reference speed which, for a passenger vehicle, is 80 km/h. (see Fig. 1).

The test track used in these tests is located in the northern road of the Miguel Hernández University of Elche and has a total length of 700 m. The measuring area is a 50 m section which fulfils the requirements established in Regulation 117 in terms of pavement characteristics and specifications of the test track in relation to the physical and construction characteristics. It is an asphalt paved area consisting of a subbase layer of 20 cm thickness of artificial gravel, 20 cm thick base of artificial gravel and a rolling layer

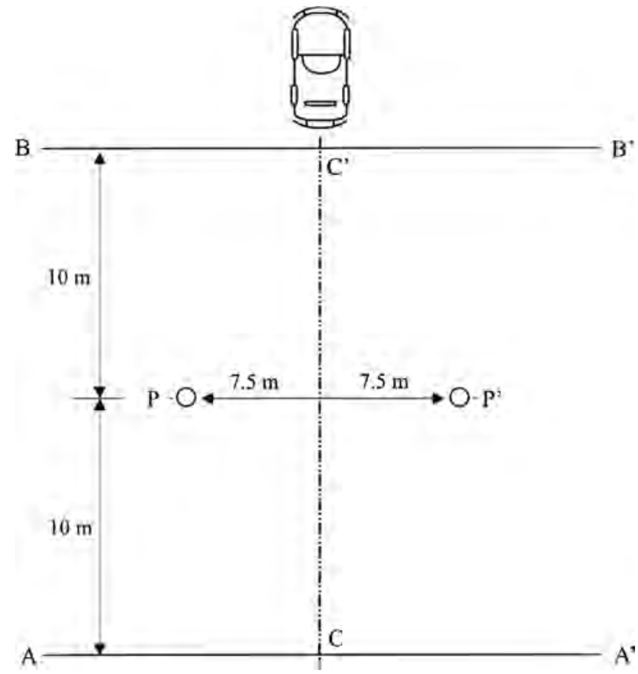

Fig. 1. Test track microphone positions.

formed by two layers, one of 5 cm of G-20 and another of 4 cm of S-20 with porphyritic aggregate, with priming and adhesion irrigations. Fig. 1 shows the microphone positions while Fig. 2 shows the test track asphalt texture, the measurement area delimited by red lines and one of the vehicles during the tests.

The maximum sound level expressed in dB(A) shall be measured as the vehicle is coasting between lines AA' and BB' (see Fig. 1 – front end of the vehicle on line AA', rear end of the vehicle on line BB'). At least four measurements shall be made on each side of the test vehicle at test speeds lower than the reference speed and at least four measurements at test speeds higher than the reference speed. The final result is obtained by a linear regression analysis for a reference speed which, as stated above, for touring vehicles' tyres is 80 km/h. According to Regulation 117, the tyre/road sound pressure level L_R in dB(A) is determined by a regression analysis according to Eq. (1):

$$L_R = \bar{L} - a \cdot \bar{\upsilon} \tag{1}$$

where $\bar{L}$ is the mean value of the tyre/road sound pressure levels, measured in dB(A):

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{2}$$

n is the measurement number ($n \geq 16$), L_i are the tyre/road sound pressure levels recorded for each measurement, $\bar{\upsilon}$ is the mean value of logarithms of speeds υ_i:

$$\bar{\upsilon} = \frac{1}{n}\sum_{i=1}^{n} \upsilon_i \quad with \quad \upsilon_i = \log\frac{V_i}{V_{ref}} \tag{3}$$

a is the slope of the regression line in dB(A):

$$a = \frac{\sum_{i=1}^{n}(\upsilon_i - \bar{\upsilon})\hat{A} \cdot (L_i - \bar{L})}{\sum_{i=1}^{n}(\upsilon_i - \bar{\upsilon})^2} \tag{4}$$

Two identical light grey and dark blue Peugeot 207 model cars were used for the tests (see Fig. 3). As prescribed by Regulation 117, both vehicles fulfilled the standard requirements:

Fig. 2. Test track measurement area and texture.

Fig. 3. Test vehicles and their external dimensions.

- The wheelbase is less than 3500 mm. (Class C1 tyres).
- They had no spray-suppression fins or any other spray-suppression devices.
- The alignment of the tyres (camber, caster and toe) was fully adjusted to the vehicle manufacturer's recommendations.
- No additional noise-absorbing material was mounted on the wheel housing or on the underside of the body.
- The suspension was in good condition, so that it did not produce an abnormal decrease in ground clearance when the vehicle was loaded in accordance with the test requirement.
- The windows of the vehicle were closed during the test.

2.1.2. Tested tyres

According to Regulation 117, all tested tyres correspond to class C1 tyres. These tyres are designed for vehicles of categories M1, O1 and O2 (Vehicles intended for the carriage of persons, up to 9 seats with a maximum mass not exceeding 3500 kg).

The following Table 1 shows the tested tyres, classified by their dimensions in three groups, while the following Fig. 4 shows all tested tyres and the sample UMH12EN002 in detail.

2.1.3. Test conditions

Requirements for test conditions are fully detailed in the CB method. Wind speed, air and track temperature, background sound level or the tyres' pressures and loads are precisely defined in Regulation 117. It prescribes that testing shall not be performed if the wind speed at the microphone height exceeds 5 m/s. Wind speed was measured at the microphone height several times, registering speeds between 0 and 1.2 m/s.

Table 1
Sample tyres classified by size.

185/65R15 88H	195/50R15 82V	205/55R16 91V
Michelin Energy	Michelin Pilot	Michelin Energy
Nexxen CP641	Nexxen CP641	Nexxen CP641
Insa Turbo Sport	Insa Turbo TVS	Insa Turbo TVS
Insa Turbo RTD2	Insa Turbo RTD2	Insa Turbo RTD2
Insa Turbo RTD3	Insa Turbo RTD3	Insa Turbo RTD3

Additionally, measurements shall not be made if the air temperature is below 5 °C or above 40 °C or the test surface temperature is below 5 °C or above 50 °C. The air temperature at the height of the microphone was also recorded during the test and temperatures between 27.2 °C at the beginning and 24.8 °C at the end were registered. As for the test surface temperature, several representative samples of the test track were taken, resulting in an average temperature between 33.8 °C at the start and 31.3 °C at the end.

Moreover, the background sound level (including any wind noise) shall be at least 10 dB(A) less than the measured tyre rolling sound emission. The background noise level did not exceed at any time 60 dB(A), which is between 12.2 and 18.9 dB(A) lower that the noise emission as measured by the Regulation in the test.

The reference load Q_r corresponds to the maximum mass associated with the load capacity index of the tyre. The test load Q_t for each tyre on the test vehicle shall be 50–90% of the reference load Q_r, but the average test load $Q_{t,avr}$ of all tyres shall be 75 ± 5% of the reference load Q_r. Taking into account the weight of both vehicles

Fig. 4. Tested tyres and detail of sample reference UMH12EN002.

as well as the load they carried along with the weight of the driver and the fuel tank, this condition was fulfilled in all tests.

Each tyre fitted on the test vehicle shall have a test pressure P_t not higher than the reference pressure P_r and within the interval:

$$P_r \cdot \left(\frac{Q_t}{Q_r}\right)^{1.25} \leq P_t \leq 1.1 \cdot P_r \cdot \left(\frac{Q_t}{Q_r}\right)^{1.25} \quad (5)$$

where P_r is the reference pressure of the tyre, Q_t is the test load for each tyre, Q_r is the reference load (the maximum mass associated with the load capacity index of the tyre), P_t is the test pressure of the tyre.

For Class C1 the reference pressure is 250 kPa for "standard" tyres and 290 kPa for "reinforced" or "extra load" tyres; while the minimum test pressure shall be > 150 kPa. In this case, the test pressure of all tyres was set to 200 kPa, since that pressure in addition to meeting the above specification, was the recommended pressure by the vehicle manufacturer for such tyres. Finally, to place the microphones, a calibrated Bosch GLM80 laser distance meter was used.

Five measurements were made on each side of the test vehicle at a test speed lower than the reference speed (70 < v < 80 km/h) and another five measurements at a test speed higher than the reference speed (80 < v < 90 km/h). In total, 20 measurements were made for each different tyre, which made a total of 300 measurements.

Given the fact that the source is in motion, there will be a displacement of the frequencies recorded by the microphones with respect to the original signal emitted by the source, that will depend on its speed. This is known as the Doppler Effect. In order to avoid that this displacement of the signal affects the results, the maximum sound pressure level L_i was recorded and analysed in third-octave bands at an integration time of 125 ms (Fast Time Weighting). Performing data processing in this way, according to [1] and [14], the error is negligible: for a sound source circulating at 100 km/h this error is approximately 0.015 dB.

Both vehicle speeds and sound spectra were recorded using a 16-channel LMS Scadas International data acquisition system. For further information about track tests instrumentation, please refer to Section 2.2.1, as the same instrumentation was used in both track and drum test methods.

Finally, the maximum sound pressure level is detected by means of data post-processing. As the data acquisition system records sound spectra during the whole test, post-processing this information using software such as Matlab or even with the data acquisition system software, makes quite easy to determine the maximum sound pressure level.

2.2. Drum tests

This section summarizes the new Alternative Drum test methodology (A-DR) which was developed to measure tyre/road sound emissions under laboratory controlled conditions. For further explanations, please refer to [3], where the methodology is widely explained.

2.2.1. Acoustic environment, instrumentation and test facilities

The drum tyre test facilities comprise a Ø1700 mm. steel 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 ram. 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 [15] for inspection bodies and ISO/IEC 17025 [16] for test laboratories since 2011. A list of the instrumentation used in both track and laboratory drum tests can be seen in the following Table 2.

Ten microphones were placed on a one-meter radius hemispherical measurement surface and were distributed according to the coordinates shown in [3] by means of different microphone stands made of aluminium Bosch profiles. The stands were placed around the tyre as seen in Fig. 5.

Correction factors K_1 and K_2 were obtained as prescribed by ISO 3744 and explained in [3]. Test results showed that both the criterion for suitability of the test environment and for the background noise were widely achieved.

2.2.2. Test configuration and tested tyres.

As the aim of this research is to validate the new methodology to measure tyre/road noise sound power level in drum test facilities, different tyres had to be tested while other factors such as surface, temperature or tyre load remained constant [17]. The tyres were tested from 40 to 120 km/h at steps of 10 km/h. A total of

Table 2
Test instrumentation employed in both track and laboratory drum tests.

Measuring instrument	Manufacturer	Model
Tachometer	RS	163–5348
Load cell	Interface	1220AJ
Microphones	Bruel & Kjaer	4935 1/4-inch
Pressure gauge	Samoa	98-ND
Thermometer	Omron	E5CN-C2MT-500
Data acquisition system	LMS International	16 channel LMS Scadas Mobile
Laser distance meter	Bosch	GLM80

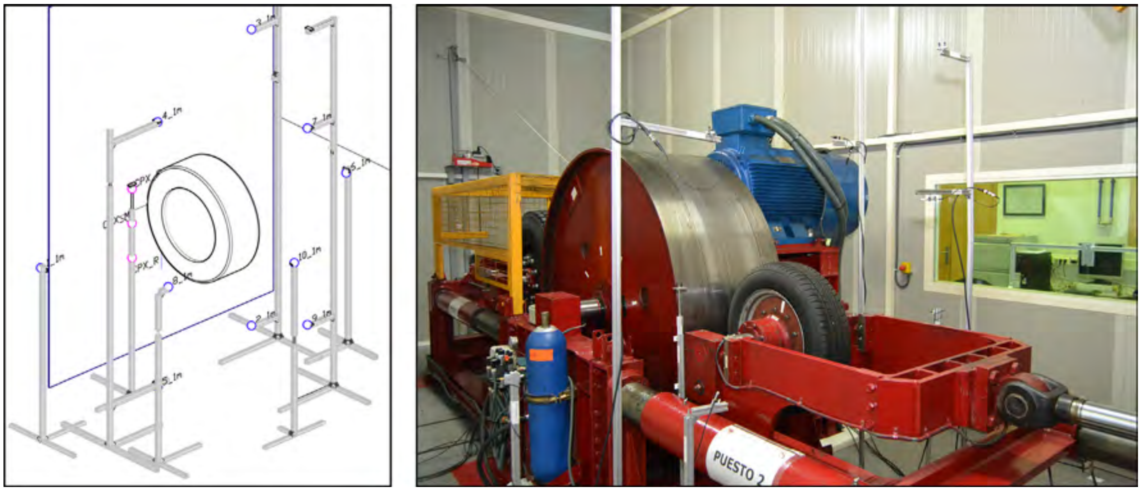

Fig. 5. Designed stands for the microphones and microphone array around the tyre.

144 different tests were carried out with the tyres and 18 additional tests registered the background noise at the same speeds.

The tyres were inflated to the nominal pressure of 200 kPa and the load applied to them was 80% of the load index as prescribed in the corresponding Regulation 117. The tyres chosen to perform the tests were exactly the same samples which had been tested before by means of the Coast-By method. All the information regarding the tyres can be seen in Section 2.1.2.

As the test room is air conditioned, the temperature was set to 25 °C while the registered temperature was kept between 24.2 and 24.9 °C. The LMS Scadas Mobile acquisition system recorded signals of 5 s between 100 Hz and 10 kHz at an integration time of 125 ms. All these data was processed in third-octave bands.

2.3. Obtaining sound pressure level L_p from sound power level L_W.

After obtaining sound power levels by means of the new Drum test method, it is possible to obtain the sound pressure level that would be registered at a distance of 7.5 m from the vehicle using the appropriate sound propagation model. This is done in order to be able to compare the results of both methods as the measured magnitudes and test conditions differ widely from one test to another.

Although there are several sound propagation models, the method specified in the ISO 9613–2 Attenuation of sound during propagation outdoors [5] is widely used in various acoustic engineering applications. In spite of the fact that its results might be less accurate than other more advanced empirical models such as Rasmussen [18] or Rudnik [19], it is a very reliable and simple model to implement. The sound propagation model proposed in the ISO 9613–2 consists of an engineering method for calculating the sound pressure level from one or more sound sources, which may be moving or stationary, such as a tyre mounted on a laboratory test bench or a vehicle in motion.

The following Eq. (6), defined by ISO 9613, calculates the equivalent continuous A-weighted sound pressure level L_p in third octave bands from the sound power level L_W.

$$L_p = L_W + D_I - A(\mathrm{dB}) \tag{6}$$

Where D_I is the directivity correction, which is set to zero at a reference height of the microphone location from the ground [20]. On the other hand, the attenuation factor A, depends on the following factors:

$$A_{total} = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc}(\mathrm{dB}) \tag{7}$$

Where A_{div},A_{atm},A_{gr},A_{bar} and A_{misc} are the attenuation due to geometric divergence, atmospheric absorption, ground attenuation, barriers or screening and miscellaneous effects respectively, and can be calculated according to [5]. Since the attenuation factor due to atmospheric absorption is different for each octave band, the total value of attenuation A_{total} will also be different for each frequency and will be determined by the sum of the previous values.

On the other hand, it is important to consider that the Coast-By track test, which registers the sound emission of four tyres, differs widely from the Drum test, where just one tyre is tested. The following Eq. (8) takes this feature into account:

$$L_p = L_W + 10 \cdot \log 4 - A_{\ total}(\mathrm{dB}) \tag{8}$$

This Eq. (8) allows calculating the sound propagation model spectrum that permits to obtain the continuous equivalent sound pressure level L_p, in third-octave bands, from the sound power level L_w measured in the Drum laboratory. The following Table 3 shows both the effect of having four tyres and A_{total} together. Therefore, the sound pressure value L_p, for each third octave band, will be the result of subtracting from the sound power value L_w , the values on this table.

3. Results and discussion

3.1. Track tests results

The sound spectra were registered through calibrated microphones and the test speeds were measured through photocells. The values of the tyre/road rolling noise level L_R were calculated from these records as explained in Section 2.1.1.

Moreover, the sound pressure level spectra in third-octave bands, between 100 and 4000 Hz, were also obtained for all 300 measurements made on the track. To do so, the data acquisition system recorded the sound spectra, at an integration time of 125 ms, during the whole test.

Afterwards, by means of data post-processing, the maximum sound pressure level spectra for each tyre was obtained. By doing so, several advantages are achieved if compared with the information obtained by means of the Regulation 117 test procedure. First of all, a spectrum gives more information than the tyre-road rolling sound pressure level L_R. Any background sudden noise or disturbance can be easily perceived in a sound spectrum while going unnoticed in a single value such as L_R.

Table 3
Sound propagation model spectrum to obtain L_p from L_w for each third-octave band.

f (Hz.)	125	160	200	250	315	400	500	630
10·log 4 – A_{total} (dB)	−20.36	−20.36	−20.36	−20.37	−20.37	−20.38	−20.39	−20.39
f (Hz.)	800	1000	1250	1600	2000	2500	3150	4000
10·log 4 – A_{total} (dB)	−20.40	−20.41	−20.42	−20.43	−20.44	−20.46	−20.48	−20.52

Besides, comparing sound spectra is much more accurate that comparing sound pressure levels. On the other hand, when we obtain L_{eq} from the sound pressure level spectra, it is not a time-dependent magnitude, which makes possible to compare track with drum test results, as the latter values are obtained in the same way, according to ISO 3744 [4].

As an example, a graph with the maximum sound pressure level spectra of different 185/65R15 88H tyres at 80 km/h is shown below (see Fig. 6):

The graphs show, in all cases, the typical tyre/road rolling noise spectrum described in the literature [1,21], where the noise values increase with the frequency with a peak at around 1000 Hz to decrease again afterwards.

Moreover, it can be seen that the two "ecological" type tyres -*Insa Turbo Ecosaver* and *Michelin Energy Saver*- are the noisiest while the conventional tyres -*Nexxen Classe Premiere* and *Insa Turbo Sport*- provide lower noise levels.

On the other hand, the equivalent sound pressure level (L_{eq}) can be obtained according to Eq. (9):

$$L_{eq} = 10 \cdot \log\left[\sum_{i=1}^{N} 10^{0.1L'_{pi}}\right] (\mathrm{dB}) \tag{9}$$

where L'_{pi} are tyre/road sound pressure levels for each third-octave band, measured in dB(A).

A comparative graph with the equivalent sound pressure level (L_{eq}) is shown below (see Fig. 7). As indicated by Fig. 7, the medium tyre size −195/50R15 88H- is the less noisy of all while the other two sizes are similar in all cases except the model Insa Turbo Eco, whose smallest size is the noisiest. It is important to mention that the specifications such as the tread pattern or the rubber compound are not the same in any of the tyres, even though among the same manufacturers' tyres.

3.2. Drum tests results

The results shown below correspond to A-weighted sound power levels for both background noise and tyre noise. One of the key aspects to be taken into account during the evaluation of the results was to analyze and compare the behavior of different microphones in order to see if their reception was affected by the test machine itself, the safety grid or any other element of the test room that could interfere with the recording of the noise level. The machine's frame or the protection grid, for example, could have caused noise reflection, shielding or diffraction that would have affected some microphones depending on their location. Even when different microphones show different sound power values at all frequencies, results have shown that this is caused by directivity of the source [22] as seen when symmetrical measurement points are compared. In fact, results are consistent, as shown in Fig. 8, where similar sound power spectra are shown, for the Nexxen Class Premiere CP461 185/65R15-88H tyre at 80 km/h, for each of the different microphones of the hemispherical measurement surface *S*.

Fig. 8 shows the typical tyre sound power spectra with an increase at about 315 Hz due to the tread of the tyre and the characteristic peak around 1 kHz. An unusual increase in noise, around 5 kHz appears due to the emission of high frequency noise from the electric motor. However, the behaviour of all the microphones has

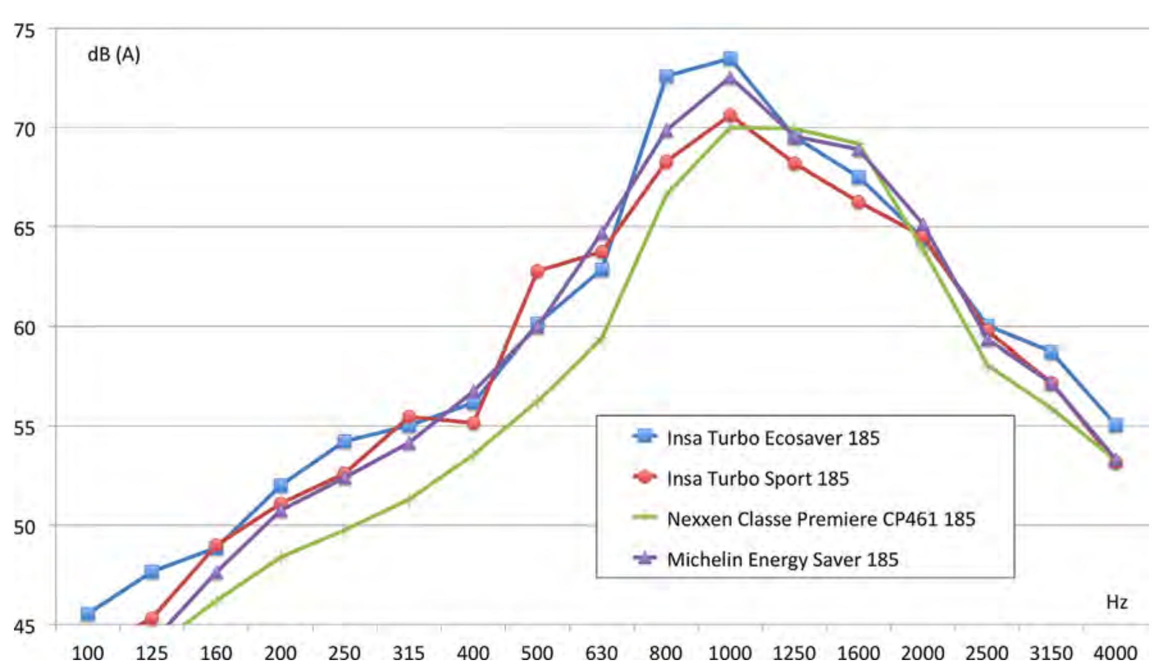

Fig. 6. Maximum sound pressure level spectra for different 185/65R15 88H tyres at 80 km/h.

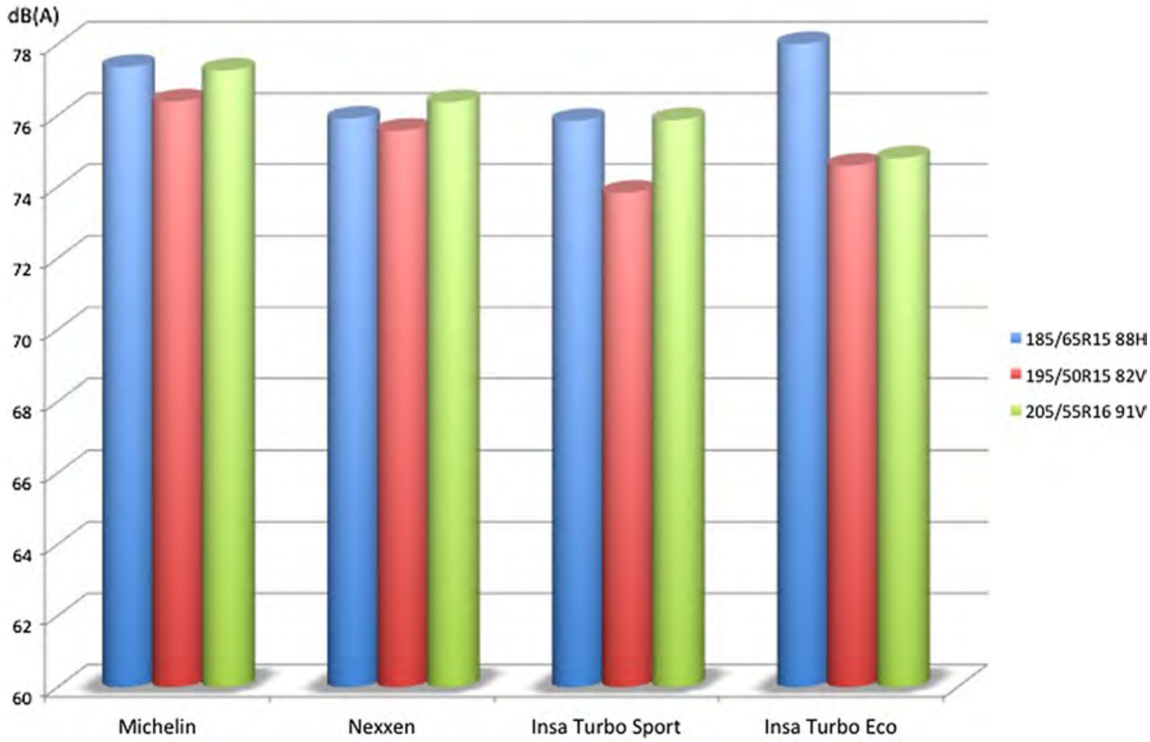

Fig. 7. Comparative graph of equivalent sound pressure levels obtained for different tyres.

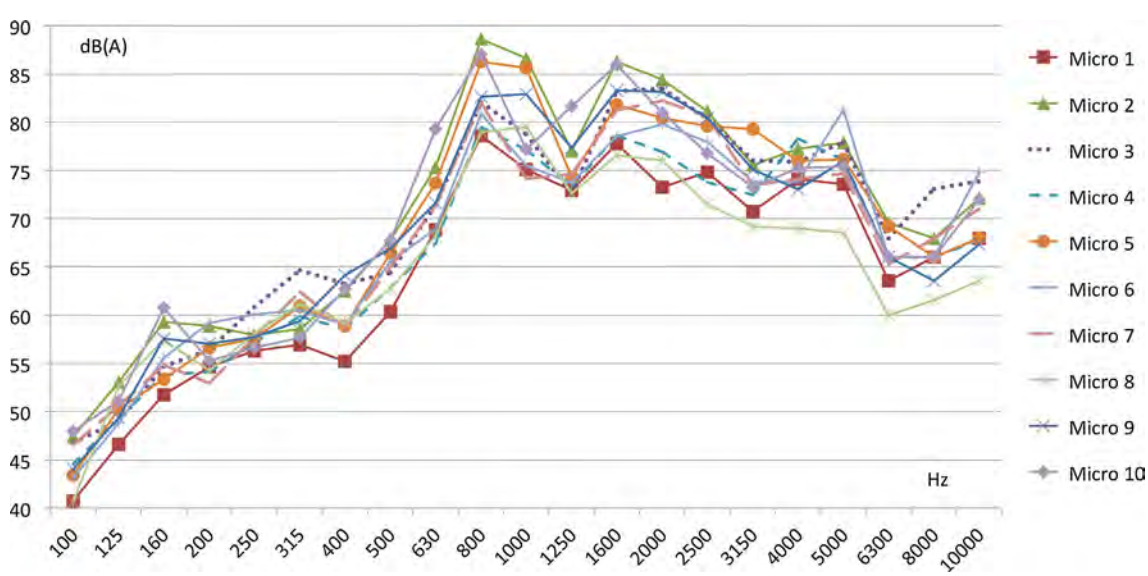

Fig. 8. Comparison of sound power spectra for each of the microphones of the hemispherical measuring surface *S*.

proven to be stable, not being able to appreciate remarkable variations between them.

Fig. 9 shows a spectrum of A-weighted sound power level in third-octave bands for a Michelin Energy Saver 185/65R15-88H tyre at 80 km/h. The red dotted line shows the overall sound power level, which includes tyre noise and drum noise when turning at 250 rpm (80 km/h for the tyre). The green dashed line shows the background noise, i.e. the noise emitted by the test bench when the drum is rotating, in this case without a tyre, at the same speed of 250 rpm. Finally, the blue solid line is the sound power level emitted by the tyre itself, which is obtained by the logarithmic subtraction of background noise to the overall sound power level.

These results are similar to those shown in the literature [1] and in other research [21] and [23]. Fig. 9 shows a typical tyre sound power spectrum in the range of 315 Hz to 4 kHz, where most of the sound energy is contained. The peak around the frequency of 1 kHz is also characteristic. Although the 5 kHz band differs from the typical tyre/road noise spectrum, this is due to the influence of the test machine, and more specifically to the electric motor which drives the whole set. However this behaviour is not a problem because the ISO 11819 CPX method [24] recommends studying tyre noise in the third octave bands located between 315 Hz and 4 kHz and the main sound emission of tyre noise is concentrated between 800 and 1600 Hz.

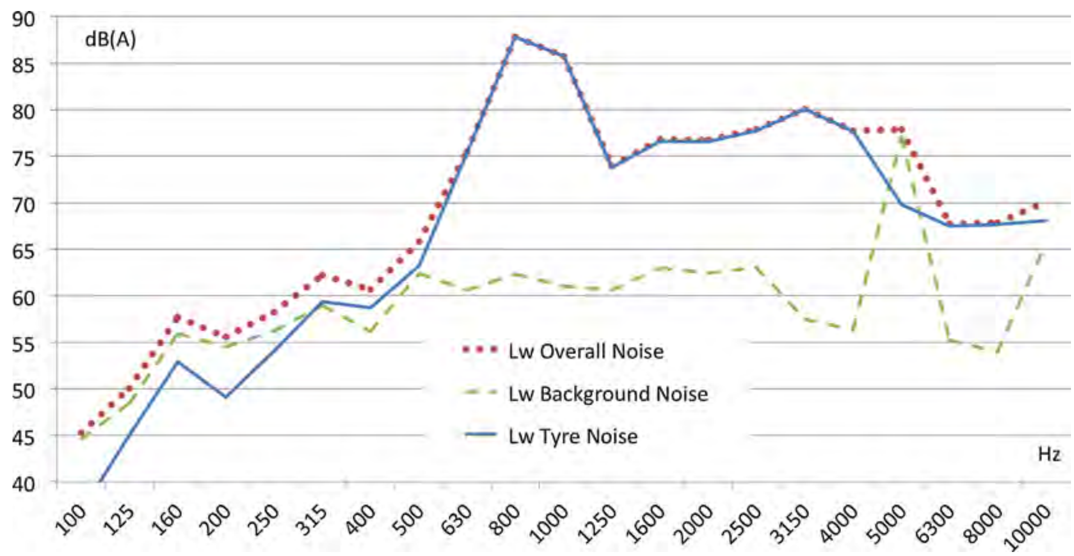

Fig. 9. Tyre sound power spectrum for a Michelin Energy Saver 185/65R15-88H at 80 km/h.

3.3. Track vs. Drum results comparison

Sections 3.1 and 3.2 have presented the results obtained in both the CB and A-DR tests. Fig. 10 shows the results of these tests together in a single graph. At the top of the graph, with an orange solid dotted line, we can see the sound power level spectrum (L_{w_Drum}) of an Insa Turbo Sport 185/65R15 88H tyre obtained by laboratory tests using the new Alternative Drum method (A-DR) at 80 km/h. Below it, we can see a cloud of dots representing the sound pressure level spectra for the same tyre obtained by different track tests ($L_{pTrack1}$ – $L_{pTrack10}$) according to the Coast-By method at speeds between 75 and 85 km/h.

Note that the spectrum shown in the Drum tests corresponds to the sound power level in the near field while in the case of the CB Track tests corresponds to the sound pressure level at 7.5 m. For this reason, there is a significant difference between the spectra obtained in both tests. As can be seen, there is a difference around 20 dB(A) between the sound power level (L_{wDrum}) recorded on the Drum tests and the sound pressure level (L_{pTrack}) recorded on the track tests. In order to compare the results obtained by both methods, it is necessary to obtain the sound pressure level L_{pDrum} at 7.5 m from the sound power level L_{wDrum} using the sound propagation method explained in Section 2.3.

3.4. Validation of the drum laboratory test method

The previous sections have shown the results obtained by means of the Coast-By track test method and the new Alternative Drum test method (A-DR). It is important to keep in mind that the values obtained in the CB track tests correspond to sound pressure levels (L_{pTrack}) at a distance of 7.5 m whereas those obtained in the laboratory Drum tests, correspond to sound power levels (L_{wDrum}) obtained according to ISO 3744 using the hemispherical measurement surface of one meter in diameter. In this section, L_{pDrum} will be obtained from L_{wDrum} using an appropriate propagation model. It is intended, therefore, to validate the laboratory drum test method explained in Section 3.

Table 4 shows, for an Insa Turbo Sport 185/65R15 88H tyre, L_{pDrum} third-octave bands sound pressure values obtained from the sound power levels L_{wDrum} as well as the difference between

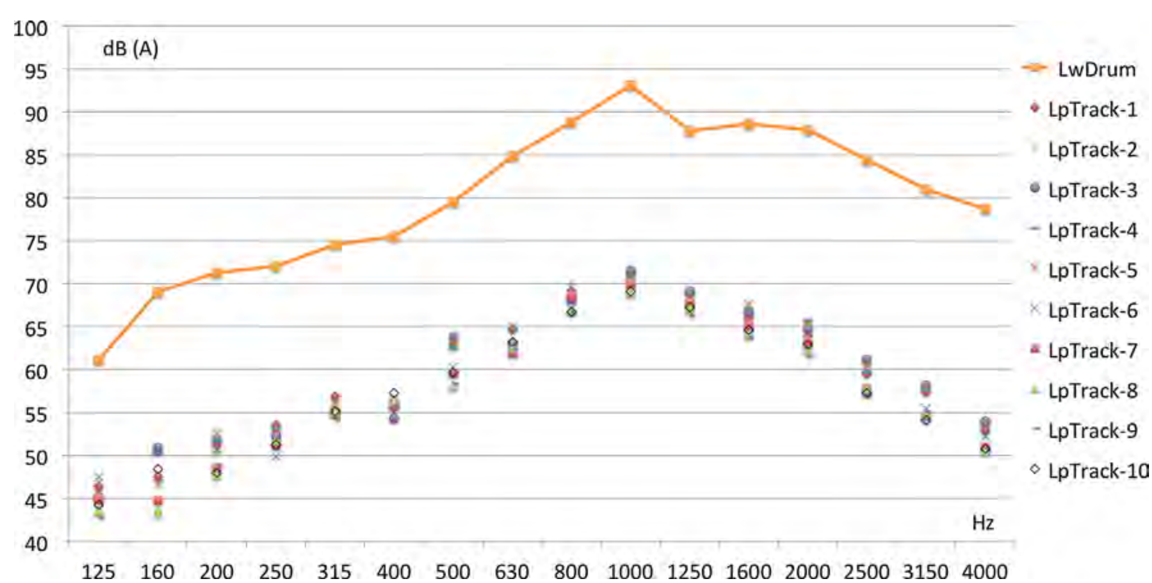

Fig. 10. Sound power level spectrum obtained in Drum laboratory tests at 80 km/h and sound pressure level spectra obtained on track tests between 75 and 85 km/h.

Table 4
L_{pDrum} third-octave bands sound pressure values and their difference with L_{pTrack} mean values.

f (Hz.)	125	160	200	250	315	400	500	630
L_{pDrum} (dB)	40.76	48.67	50.94	51.65	54.19	55.10	59.16	64.45
$L_{pDrum} - L_{pTrack}$ (dB)	−4.10	0.61	1.21	−0.05	−0.71	−0.38	−1.58	1.63
f (Hz.)	800	1000	1250	1600	2000	2500	3150	4000
L_{pDrum} (dB)	68.43	72.67	67.34	68.18	67.50	64.00	60.52	58.20
$L_{pDrum} - L_{pTrack}$ (dB)	0.93	2.73	−0.17	3.04	4.21	5.65	4.76	6.32

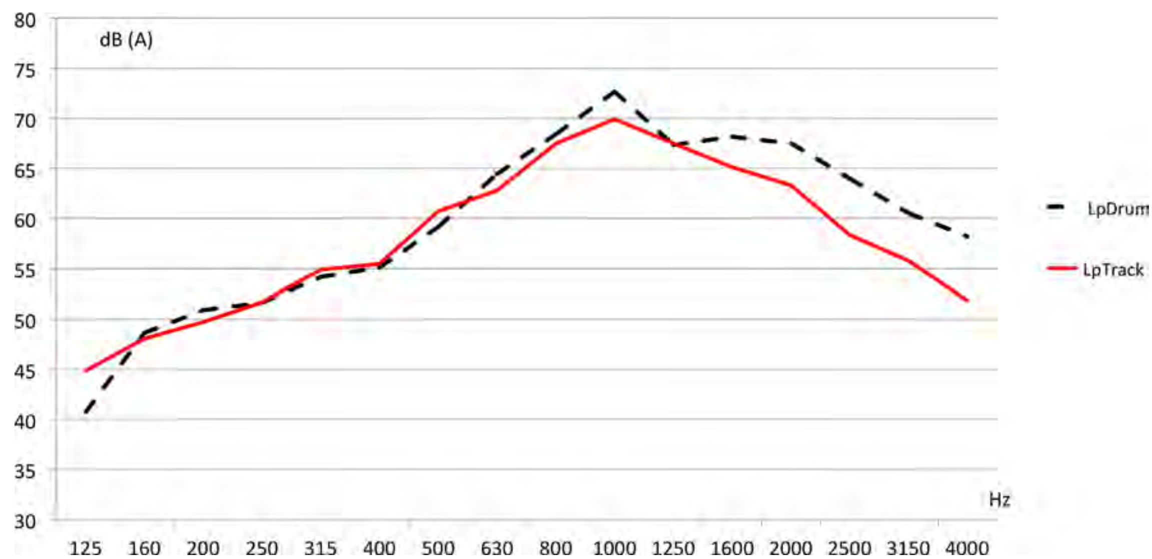

Fig. 11. Comparison between the Coast-By sound pressure level L_{pTrack} and the sound pressure level L_{pDrum} obtained from the sound power level L_{wDrum} for a Insa Turbo Sport 185/65R15 88H tyre.

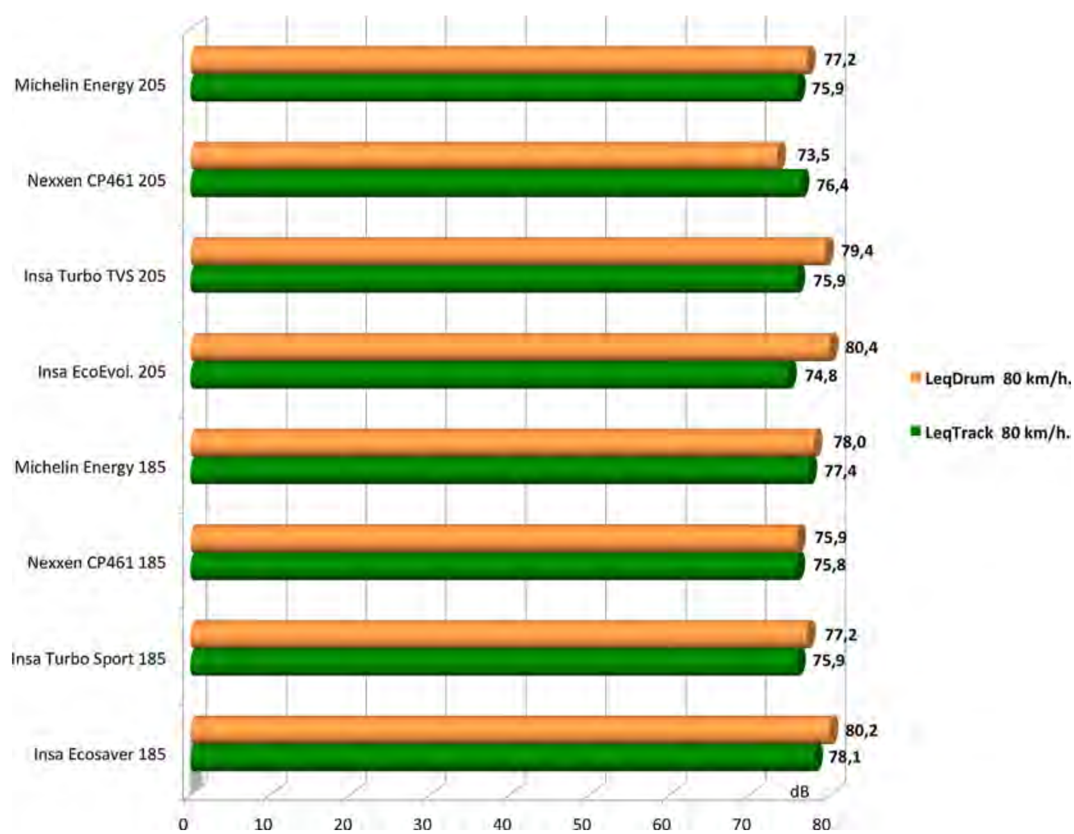

Fig. 12. Comparison between the L_{eqDrum} sound pressure levels obtained in the Drum tests and the $L_{eqTrack}$ sound pressure levels recorded in the Coast-By track tests.

these values and the mean value of the sound pressure L_{pTrack}, calculated according to [2] by means of the Coast-By method.

In the frequency range between 2 and 4 kHz there is a difference between 4 and 6 dB. However, this difference is not very significant if we evaluate the equivalent sound pressure levels L_{p_eq}, which are the values considered in type approval (see Fig. 12).

Besides, Fig. 11 shows the sound pressure level L_{pDrum} (black dashed line) obtained from L_{wDrum} on the Drum test for a Insa Turbo Sport 185/65R15 88H tyre at a speed of 80 km/h considering the effect of four tyres and the attenuation obtained by the sound propagation model described in Section 2.3. It also shows a comparison between the Coast-By sound pressure level L_{pTrack}. As can be seen, the sound pressure level spectrum L_{pDrum}, shows a reasonable similarity with the sound pressure level spectra mean values L_{pTrack} (red solid line), specially in the frequency range between 125 and 2000 Hz.

In addition, it is possible to obtain the equivalent sound pressure level L_{eq} with the previous Eq. (9). Using the values shown in Table 4 for each third-octave band frequency, the equivalent sound pressure value L_{eqDrum} obtained from the Drum tests for the Insa Turbo Sport 185/65R15 88H tyre is $L_{eqDrum} = 77.2\text{dB(A)}$. On the other hand, the equivalent sound pressure value $L_{eqTrack}$ obtained from the mean sound pressure value of the track tests for the same tyre according to the Coast-By method is $L_{eqTrack} = 75.1\text{dB(A)}$.

Comparing the equivalent sound pressure values obtained by both methods for all the tyres tested, the mean value of these differences is $\overline{\Delta L_{eq}} = 1.98\text{dB(A)}$. This value is similar or even significantly lower than other deviations obtained during different track tests according to the conventional method described in Regulation 117 and whose estimations have been previously published by other authors and are reported in [13]. These deviations have been classified as deviations due to factors such as the test track (3–9 dB), the vehicle (1.6 dB) or the test temperature (2 dB).

Finally, Fig. 12 shows, for all test tyres, the $L_{eqTrack}$ sound pressure results obtained during the CB track tests as well as the L_{eqDrum} sound pressure level results obtained in the A-DR Drum tests. The results obtained in all cases are very similar, with differences around 2 dB(A) between the CB track tests and the tests carried out with the new Alternative Drum methodology (A-DR). As explained before, these differences are acceptable and similar to those shown in other research.

4. Conclusions

The CB method is quite an expensive test. It needs a vehicle and four tyres which need to be fitted on it. There is neither a vehicle nor a rim size which fits on every tyre size in the market, so the CB method needs more than one vehicle and different rim sets. Moreover, at least two people must be working on the test at the same time and a considerable amount of fuel is consumed during the tests. Finally, track tests need a lot of time to be carried out, which makes them expensive. All these factors make conventional methods more expensive than the alternative methodology proposed in this paper.

Moreover, the most important limitation of conventional track methods is the measured magnitude, the sound pressure level [3]. It is well known that sound pressure level depends on several factors such as the environment in which sound waves travel, attenuation or distance from the noise source. This does not happen to the sound power level, which is a magnitude that is inherent in the noise source and does not depend on other external factors [23]. Therefore, by measuring sound pressure it is not possible to quantify the sound power of the source unless the environment is strictly controlled and defined. This does not occur in the methodology described in Regulation 117 or in any other of the conventional methods previously mentioned.

After analysing the results obtained by means of the A-DR method, we can conclude that the laboratory test method not only is reliable in terms of reproducibility, but its results also coincide with those obtained experimentally using conventional track test methods. Furthermore, once the characterization of the tyre test facilities 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) [4].

For these reasons, it can be said that tyre sound emission tests carried out at the Drum test facilities are valid for obtaining sound power levels L_W and that these values correspond to the results obtained by other research groups in drum facilities and 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 [3]. In addition to this, as seen from the results, the study of a rolling tyre against the drum should be focused on the range from 315 Hz to 4000 Hz, as it contains the most important information of noise emission while avoiding noise disturbances that occur at high frequencies which, on the other hand, contain little sound energy and can be left out.

On the other hand, using the sound propagation model proposed in ISO 9613, it is possible to determine the sound pressure level L_{pDrum} from the sound power level L_{wDrum} measured in the Drum tests. After using this model, it has been demonstrated that the sound pressure values obtained from the sound power levels measured in the Drum tests are very similar to those registered by the conventional Coast-By track test method $L_{pTrack.}$

Furthermore, the difference between the equivalent sound pressure values L_{eqDrum} obtained in the laboratory Drum tests and the equivalent sound pressure values $L_{eqTrack}$ calculated from 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 have shown 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 demonstrates the validity of the new Drum test methodology.

Even when some drum test results, such as the speed coefficient A explained in [3], are different when compared to the track tests data reported in [1], results have proved to be satisfactory. This behaviour may be caused due to the smoothness of the drum surface which contrasts with the rough road surfaces, where conventional methods are carried out. Moreover, this research does not evaluate the sound pressure but the sound power emitted by a rolling tyre using a new methodology that combines the International Standard ISO 3744 and a Drum tyre test facility in order to improve the results obtained by the method described in Regulation 117 or by other conventional methods. Hence, the new drum test method is not meant to be an equivalent test to the conventional track tests, but it has been developed to become a more accurate, alternative test.

This new Alternative Drum test method (A-DR) has been validated not only by comparing its results with those obtained in the track tests carried out by the Mechanical Engineering research group of the Miguel Hernández University of Elche, but also with the results obtained by other methods, both on track and drum facilities, by several research groups during the last decades. In addition, the relationship between the sound power level obtained by the new method and the sound pressure level recorded in the track tests following the conventional CB method, has been verified using the sound propagation model established in the International Standard ISO 9613.

The A-DR test methodology has proved to be valid, repeatable and accurate, with lower uncertainty values than the current homologation test. In addition, the essential parameters of the test are more controllable than those of the Coast-By test so the new method allows less variability and, therefore, greater reproducibility. Results have shown that both methods are not only comparable but also have remarkably similar sound spectra and, for that reason, the new methodology based on drum tests should be considered as an alternative method to the conventional CB method for type approval of tyres. In addition, with this method both the whole noise spectrum and the value of equivalent sound power level could be obtained.

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