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A New CPX Drum Test to Obtain Sound Pressure Levels of Tyre Noise for Type Approval

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Abstract: The primary cause of noise from vehicular traffic while travelling at speeds over 30 km/h is tyre/road interaction. To reduce this noise source, tyre/road sound emissions research has been carried out using different approaches. Most of this research has been centred around track tests, leading to the development of various track and road-based methods for evaluating tyre/road noise emissions. The CPX (Close-Proximity), along with the CPB (Controlled Pass-By), the CB (Coast-By) and the SPB (Statistical Pass-By), methods are the most common ones. Nevertheless, since Reg. (EC) 1222/2009 came into force, only the CB method, defined in Reg. (EC) 117/2007, can be used to obtain tyre/road noise emission type approval values in Europe. However, current track test methods have important limitations, such as the variability of the results depending on the test track or the test vehicle, the repeatability, the influence of environmental variables or, the main aspect, the limitation of the registered magnitude in these tests, which is the sound pressure level. The Alternative Drum test method (A-DR) was developed in 2015 in order to avoid these disadvantages. However, it involves a complex and time-consuming microphone array for each test. With the purpose of improving the A-DR test method, a new methodology based on drum tests, the ISO 11819-2 and the ISO 3744 standards, was developed. This paper describes the new Alternative CPX Drum test method (A-CPX-DR) and validates it by testing several tyres according to the CB, the A-DR and the A-CPX-DR test methods and comparing their results. This research has demonstrated that all three methods have equivalent sound spectra and obtain close equivalent sound pressure levels for type approval of tyres in the EU, while drum tests have shown greater accuracy. For both reasons, the new A-CPX-DR methodology could be used for tyre/road noise emission type approval in a more precise and cheaper way.

Keywords: Alternative Drum method; Close Proximity method; tyre; noise; drum; sound power

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1. Introduction

Tyre/road sound emissions are the main source of noise for an ICE vehicle travelling at medium and high speeds. Over 30 km/h, the impact of other noise sources, such as the engine, the exhaust system or the drivetrain, within the whole vehicle noise is very limited [1]. This behaviour happens practically from a standstill in battery electric vehicles, as electric motors, inverters and transmissions are almost silent [2]. Consequently, in order to reduce road traffic noise, tyre/road sound emissions need to be addressed.

The EU published Reg. 117 [3] in 2007, Reg. 661 [4] and Reg. 1222 [5] in 2009, and Reg. 740 [6] in 2020, in order to reduce tyre/road sound emissions. Regulation 117 defines the methodology to obtain sound pressure levels (SPLs) for tyre/road noise emissions, while Reg. 661 sets limits on the external rolling noise of tyres to be on the market under CE type approval. Finally, Reg. 1222 and Reg. 740 establish a classification of tyres according to their noise emission.

Several methods, such as the CPX (Close-Proximity) along with the CPB (Controlled Pass-By), the CB (Coast-By) and the SPB (Statistical Pass-By) methods were developed to evaluate tyre noise emissions. Nevertheless, as stipulated in Reg. 117, the CB method is the only approved means to obtain values for tyre/road noise emissions in the EU.

However, these conventional track methods have several restrictions and disadvantages. The first limitation involves not only the test track but also the test vehicle, as its influence on the test results has been proven to be significant [7,8]. In fact, it is considerably more difficult to obtain similar values when the tests are performed by several laboratories on different tracks [9] or with different test vehicles [10]. Because of the wide range of factors that can affect the test results, repeatability is also an issue, even when the tests are carried out by the same laboratory with the same vehicle and on the same track. Moreover, environmental factors such as background noise, temperature and wind, or variations in the test vehicle or on the test track as time passes, make an important contribution to the test results and cannot be quantified with ease [7,11,12]. Finally, several studies claim that results can be considerably affected by real test speeds, vehicle categories or because of the effect of pavement ageing or differences in surface roughness [13–15].

On the other hand, research on measurement uncertainty in track tests has found that the limitations of each of these factors can lead to differences in the test results of up to 4 dB [8,16]. These differences can be even much higher, as all—or most—of these factors play an important role in each measurement at the same time. For these reasons, the repeatability and reproducibility of conventional track test methods can be said to be far away from a scientific method for type approval of tyres in the EU [7,17].

In this context, the Alternative Drum test method (A-DR) [18,19] was engineered to overcome these limitations and was evidenced to be more accurate and repeatable than the CB method. Even though the main objective was widely achieved, a complicated and time-consuming microphone array setup is needed to carry out each A-DR test. For this reason, a new drum methodology, called the Alternative CPX Drum (A-CPX-DR) test method was developed. Based on the expertise of the A-DR test method, and the ISO 11819-2 [20] and ISO 3744 [21] standards, it applies a standardized specific engineering method for determining sound power level and consists of a much easier test configuration, while the results are even more accurate than the ones obtained previously with the A-DR.

Tyre noise emissions have been assessed previously by measuring sound pressure levels on drums [16,22,23]. The same magnitude is measured in the CB test method established in Reg. 117. However, SPL is a magnitude that depends on several environmental factors and the distance between the receiver and the noise source. For this reason, unless test conditions are precisely defined, measured and controlled, it is impossible to assess the sound power of the source by measuring sound pressure levels. This can be addressed by obtaining the sound power level under laboratory-controlled conditions, which is an inherent magnitude in the noise source that is independent of such external factors [24].

This paper explains the methodology and test configuration to carry out the new A-CPX-DR test method and validates it by testing a wide range of tyres according to the CB, the A-DR and the A-CPX-DR test methods and comparing their results. As previously performed in the A-DR test method, to validate the new methodology, the standardized ISO 9613 [25] sound propagation method was used to calculate the SPL at 7.5 metres from the sound power level of a tyre measured under laboratory-controlled conditions when rolling against a drum. Finally, the test results are compared and discussed, reaching several interesting conclusions.

2. Materials and Methods

2.1. Regulation (EC) 117/2007 Standardized Coast-By Track Tests

This section summarizes the test conditions and set-up in order to obtain tyre/road noise emissions for a series of tyres using the standardized Coast-By track test method. For further explanations, please refer to Regulation (EC) 117/2007 and [19], where the methodology is explained.

2.1.1. Coast-By Test Procedure

The CB method assesses the noise level of tyres fitted on a vehicle as it travels on a standardized testing track. Two microphones (P-P'), placed at a distance of 7.5 m on both sides of the track reference line CC' and 1.2 m above the ground, register the maximum sound pressure level when the vehicle is coasting (see Figure 1).

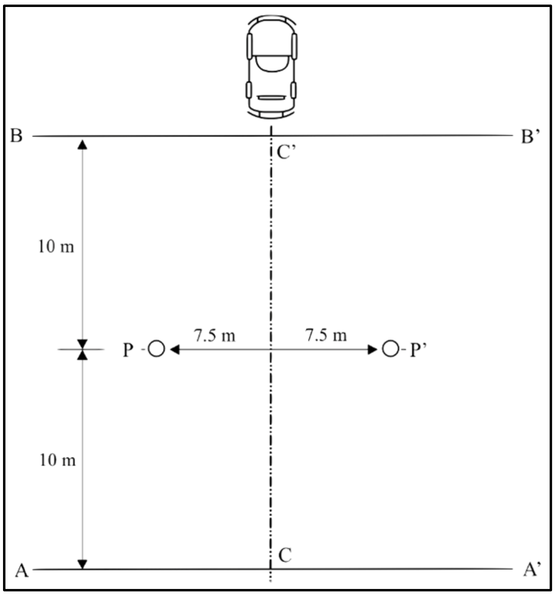

Figure 1. Microphone position set-up on the test track. Source: Regulation (EC) 117/2007.

The reference speed for passenger vehicle tyres is 80 km/h. A minimum of four measurements must be registered, on either side of the vehicle, at speeds over 80 km/h. The same must be done at speeds under the above-mentioned speed. The result is then calculated by linear regression. As established in Reg. 117, the SPL (L_R) measured in A-weighted dB is obtained using the following Equation (1):

$$L_R = \overline{L} - a\cdot\, \overline{v}\ \text{dB} \tag{1}$$

where $\overline{L}$ is the tyre/road SPL average value:

$$\overline{L} = \frac{1}{n}\sum_{i=1}^{n} L_i\ \text{dB} \tag{2}$$

n is the number of measures (at least 16),

L_i are the registered tyre/road SPLs,

$\overline{v}$ is calculated as the average of logarithms of speeds v_i:

$$\overline{v} = \frac{1}{n}\sum_{i=1}^{n} v_i\ with\ v_i = \log\frac{V_i}{V_{ref}} \tag{3}$$

a is the slope of the regression line:

$$a = \frac{\sum_{i=1}^{n}\left(v_i - \overline{v}\right)\cdot\left(L_i - \overline{L}\right)}{\sum_{i=1}^{n}\left(v_i - \overline{v}\right)^2}\ \text{dB} \tag{4}$$

2.1.2. Tested Tyres

All the tyres tested were class C1 tyres, as established by Regulation 117, which are used in passenger vehicles (categories M1, O1 and O2). Table 1 displays all the tyres which were tested, categorized by their nominal dimensions, whilst the subsequent Figure 2 illustrates all the tested tyres, including a detailed view of one of them.

Table 1. Tested tyres and their nominal dimensions.

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 Ecosaver	Insa EcoEvolution	Insa EcoEvolution
Insa Turbo RTD3	Insa Turbo RTD3	Insa Turbo RTD3

Figure 2. Tyre tread patterns of some of the tested tyres.

2.1.3. Coast-By Test Conditions

The Coast-By test environmental requirements are thoroughly described in Regulation 117. Factors such as air or track temperature limit, maximum background sound level or wind speed or the tyre's loads and pressures are specified for the CB method. The following Table 2 summarizes the requirements and the test conditions in which the track tests were carried out:

Table 2. Requirements and test conditions.

	Requirement	Test Conditions
Wind speed (m/s)	<5	0–1.2
Air temperature (°C)	$5 < T < 40$	24.8–27.2
Surface temp (°C)	$5 < T < 50$	31.3–33.8
Background sound level (dB)	$<SPL_{Measured} - 10$ dB	12.2–18.9

2.1.4. Test Track Specifications

The test track, which spans a total distance of 700 m, is situated in the Miguel Hernández University of Elche's campus. The measurement area is a 50 m section fulfilling all the specifications and pavement requirements determined in Regulation 117. The test track is an asphalt-paved surface which consists of four layers: a 200 mm thick subbase of artificial gravel; 200 mm of artificial gravel base; a rolling layer consisting of a 50 mm subbase of G20; and a 40 mm base of S20 with porphyritic aggregate. Figure 3 shows the measurement area, while the asphalt texture can be seen in Figure 4. For additional information about the test track pavement, please refer to [26], where it is characterized.

2.2. Alternative Drum Tests

This section briefly reviews the A-DR method, which was validated in 2015 to obtain sound pressure levels for type approval of tyres under a controlled environment using a 10-microphone array setup. It also explains in detail the new Alternative CPX Drum (A-CPX-DR) test methodology microphone array, considering that the rest of the measurement procedure is exactly the same as in the A-DR test method. For further explanations, please refer to [18], where the methodology and the measurement procedure are explained.

Figure 3. Test track measurement area.

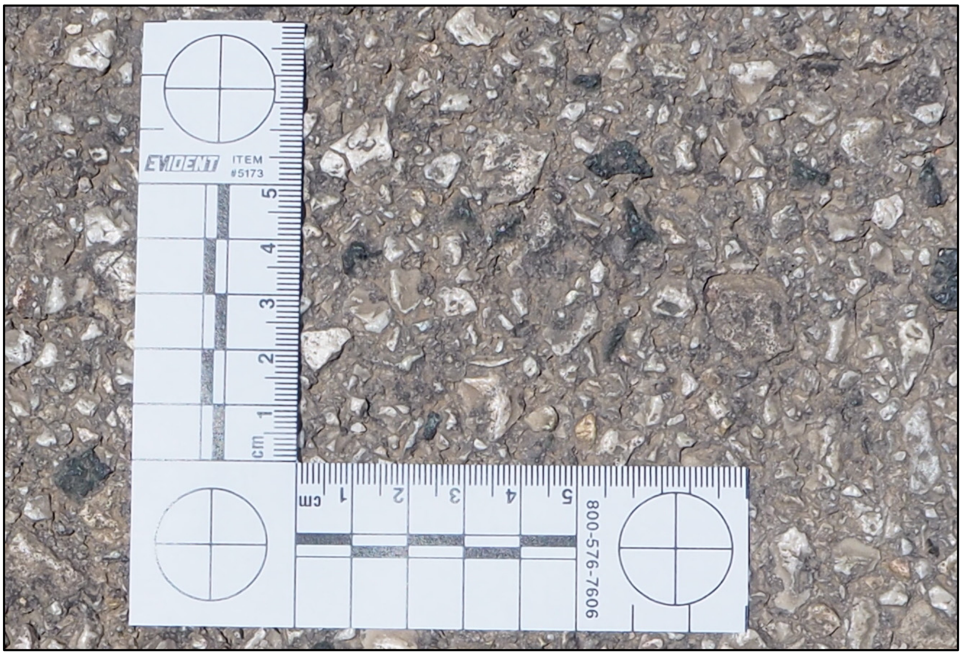

Figure 4. Test track asphalt texture.

2.2.1. Drum Test Facilities, Instrumentation and Requirements for Acoustic Environment

The test facilities in which the Alternative Drum tests were carried out consist of a testing chamber constructed from sound-absorbing materials. Its dimensions are 3.92 × 9.35 × 4.84 m. The test drum surface is made of smooth steel with a diameter of 1700 mm. Measuring instruments are calibrated yearly, while the laboratory has been accredited annually since 2011 by an ILAC International Accreditation Body as fulfilling the international standards ISO 17025 [27] for test laboratories and ISO 17020 [28] for inspection bodies. The measuring instruments used in all the tests are shown in Table 3.

The criteria for background noise (K_1) and suitability of the test environment (K_2) correction factors were obtained according to ISO 3744 as described in [18]. The test results revealed that both K_1 and K_2 requirements were fulfilled, as can be seen in Table 4.

Table 3. Measuring instruments used in Alternative Drum and CB track tests.

Test Instrumentation	Supplier	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

Table 4. ISO 3744 requirements and test results for correction factors.

	ISO 3744 Requirement	Acoustic Environment
Limitation for background noise	$K_1 < 1.3$ dB	0.22 dB
Suitability of the test environment	$K_2 < 2$ dB	0.70 dB

2.2.2. A-DR and A-CPX-DR Microphone Array Setup

Ten microphones were used for the Alternative Drum (A-DR) tests. They were positioned on a measurement surface, of hemispherical shape and a one-meter radius, following the coordinates established in ISO 3744, as explained in [18], using different stands arranged around the tyre as shown in Figure 5.

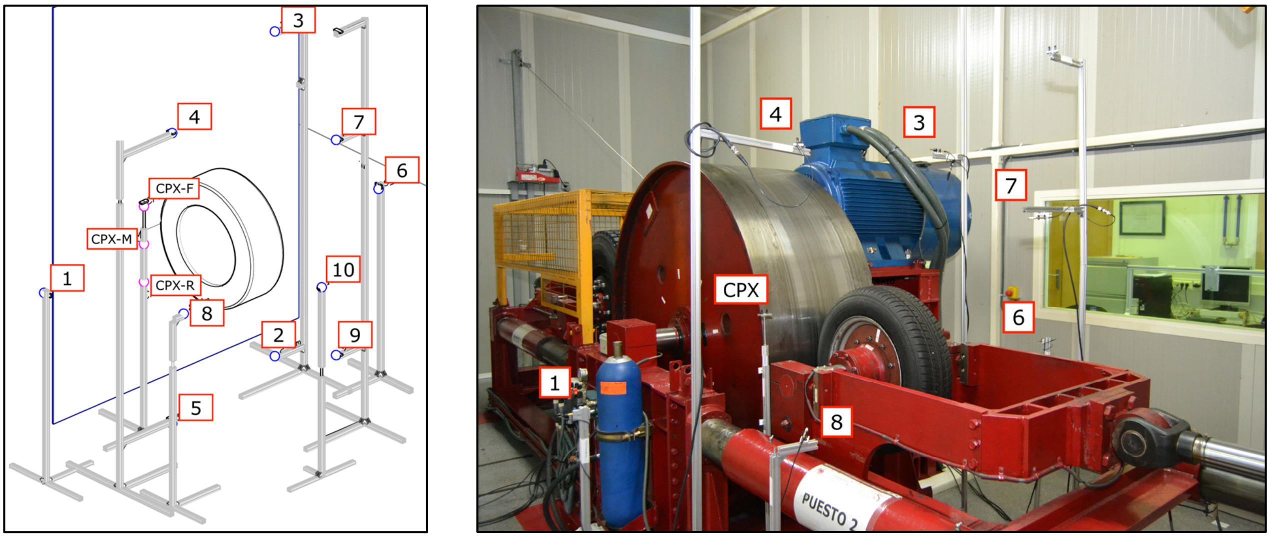

Figure 5. Microphone array around the tyre, according to ISO 3744, for the A-DR tests.

For the Alternative CPX Drum (A-CPX-DR) tests, three microphones were positioned around the tyre, according to the ISO 11819-2 standard, using an aluminium Bosch profile microphone stand, as can be seen in Figure 6.

2.2.3. Alternative Drum Tests Configuration

To validate the new A-CPX-DR method, the tyres were tested according to the A-DR and the A-CPX-DR test methods, while factors such as the tyre load, the test temperature or the surface, were the same for all the tests [29]. A total of 135 tests were conducted on 15 different tyres, at speeds between 40 to 120 km/h in 10 km/h increments. Additionally, 18 measurements were carried out on the background noise while the whole drum equipment was working within the same speed range with no tyre rotating against the drum.

The tested tyres were the same units which had been used before in the Coast-By track tests. As prescribed in Regulation 117, each tyre's nominal pressure was set to 200 kPa, while its load was adjusted to 80% of its load capacity index.

The test temperature was 24.5 ± 0.5 °C. Sound power spectra were registered in 5 s. intervals, at an integration time of 125 ms, and analysed in third-octave bands.

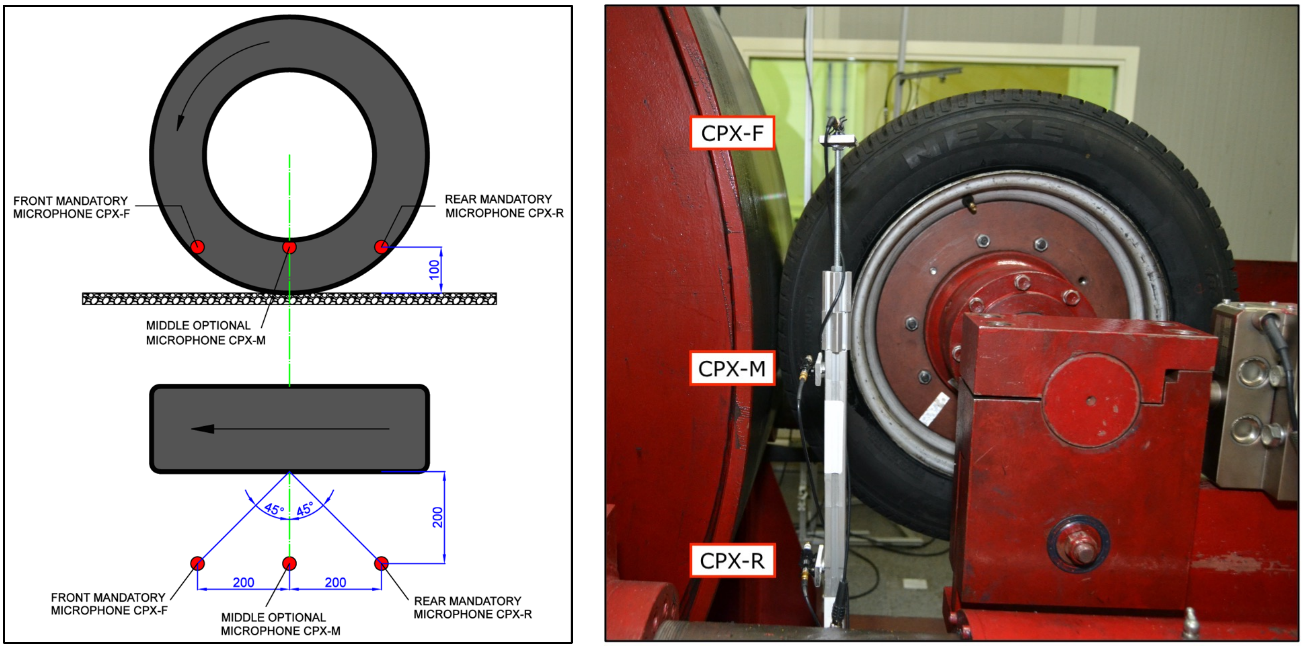

Figure 6. Microphone array around the tyre for the A-CPX-DR tests.

2.3. *Procedure to Calculate Sound Pressure Level from Sound Power Level*

Once sound power levels are registered in the drum tyre test facilities, the sound pressure levels, in CB conditions, can be obtained using a sound propagation model. In this case, ISO 9613-2: Attenuation of sound during propagation outdoors was used.

Even though there are several sound propagation models, the ISO 9613-2 method is widely used in acoustic engineering applications. Although it can be less accurate than other, more advanced empirical models, such as Rudnick [30] or Rasmussen [31], it is a simple, reliable and easy model to implement. The ISO 9613-2 sound propagation model is an engineering method for calculating the SPL from one or more, stationary or moving sound sources, such as a tyre mounted on a test drum or a moving vehicle, as can be seen in [32].

ISO 9613-2 defines Equation (5) to obtain the equivalent continuous SPL from the sound power level.

$$L_p = L_W + D_I - A \text{ dB} \tag{5}$$

where D_I is the directivity correction. At the microphone's height of 1.2 m, this factor is zero [26]. The total attenuation factor can be obtained by the following Equation (6):

$$A_{total} = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \text{ dB} \tag{6}$$

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 obtained according to ISO 9613-2. Only A_{atm} is different for each octave band. The rest of the attenuation factors are frequency-independent. For this reason, there are no significant differences between each third-octave band in the total attenuation factor, A_{total}.

Moreover, it must be taken into account that CB track tests, which register the sound emission of 4 tyres, vary considerably from the Alternative Drum and Alternative CPX Drum tests, where only one tyre is tested. The following Equation (7) takes this into consideration:

$$L_p = L_W + 10 \cdot \log 4 - A_{total} \text{ dB} \tag{7}$$

This Equation (7) permits obtaining the propagation model spectra that allows to calculate the continuous equivalent SPL, from the sound power level obtained in both the A-DR and A-CPX-DR tests.

Table 5 shows the influence of having four tyres and the total value of attenuation at the same time. To obtain the sound pressure values L_p, the values on this table must be subtracted to the sound power values L_w for each third-octave band.

Table 5. Sound propagation model spectrum to obtain L_p from L_w.

f (Hz)	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**
$10{\cdot}\log 4 - A_{total}$ (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**
$10{\cdot}\log 4 - A_{total}$ (dB)	−20.40	−20.41	−20.42	−20.43	−20.44	−20.46	−20.48	−20.52

3. Results and Analysis

3.1. Coast-By Track Test Results

Tyre/road rolling noise level values L_R were calculated from the data measured by the microphones in accordance with Reg. 117. Additionally, the SPL spectrum was also calculated for the values registered on the track. The sound spectra were registered in 5-second intervals with an integration time of 125 ms. The maximum SPL spectra were then determined for each tyre.

This approach offers several significant advantages compared to the information provided by the CB test procedure established in Regulation 117. Firstly, a sound spectrum provides much more data than the SPL by itself. Background noise is easily identified in a whole sound spectrum, whereas it can be masked in a value such as L_R. Furthermore, it is more accurate to compare sound spectra than to compare sound pressure levels. Finally, obtaining L_{eq} from the SPL spectra, which is a time-independent magnitude, enables the comparison of CB with A-DR and A-CPX-DR test results, as these values are obtained in this way in accordance with ISO 3744.

The SPL spectra of several tyres, obtained using the CB track tests, can be seen in the following Figure 7:

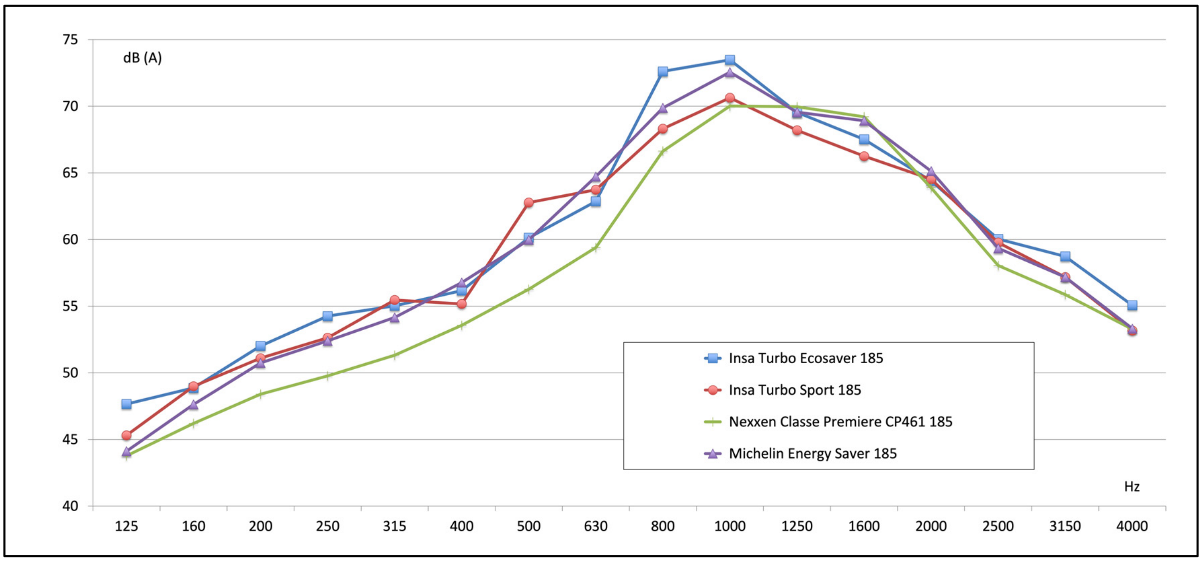

Figure 7. Different 185/65R15 88H tyre maximum sound pressure level spectra (test speed: 80 km/h).

The characteristic tyre/road rolling noise spectrum is shown in Figure 7, as described in [1,33]. Noise values show a gradual increase with frequency, reaching a peak at 1 kHz and decreasing thereafter.

3.2. Alternative Drum and Alternative CPX Drum Tests Results

The results in this section for both the Alternative Drum and the Alternative CPX Drum test methods correspond to A-weighted sound power levels.

Figure 8 shows the sound power level obtained in both the Alternative Drum tests, $L_{w\ A\text{-}DR}$ (orange line with rhomboidal marker type), and in the Alternative CPX Drum tests, $L_{w\ A\text{-}CPX\text{-}DR}$ (green line with square marker type), for an INSA Turbo Sport 185/65R15 88H tyre at 80 km/h. The typical tyre sound power spectra with the characteristic peak around 1 kHz, as described in the literature and registered in the Coast-By track tests, were also obtained in both Drum tests. However, there is a significant difference in the lower third-octave bands between the spectra of the A-DR and the A-CPX-DR methods. There are also differences in other frequencies, such as in 1 and 2 kHz. The results seem to be affected by the tyre's sound emission directivity, which is caused by the difference between microphone positions and their distance to the noise source for each Alternative Drum test method.

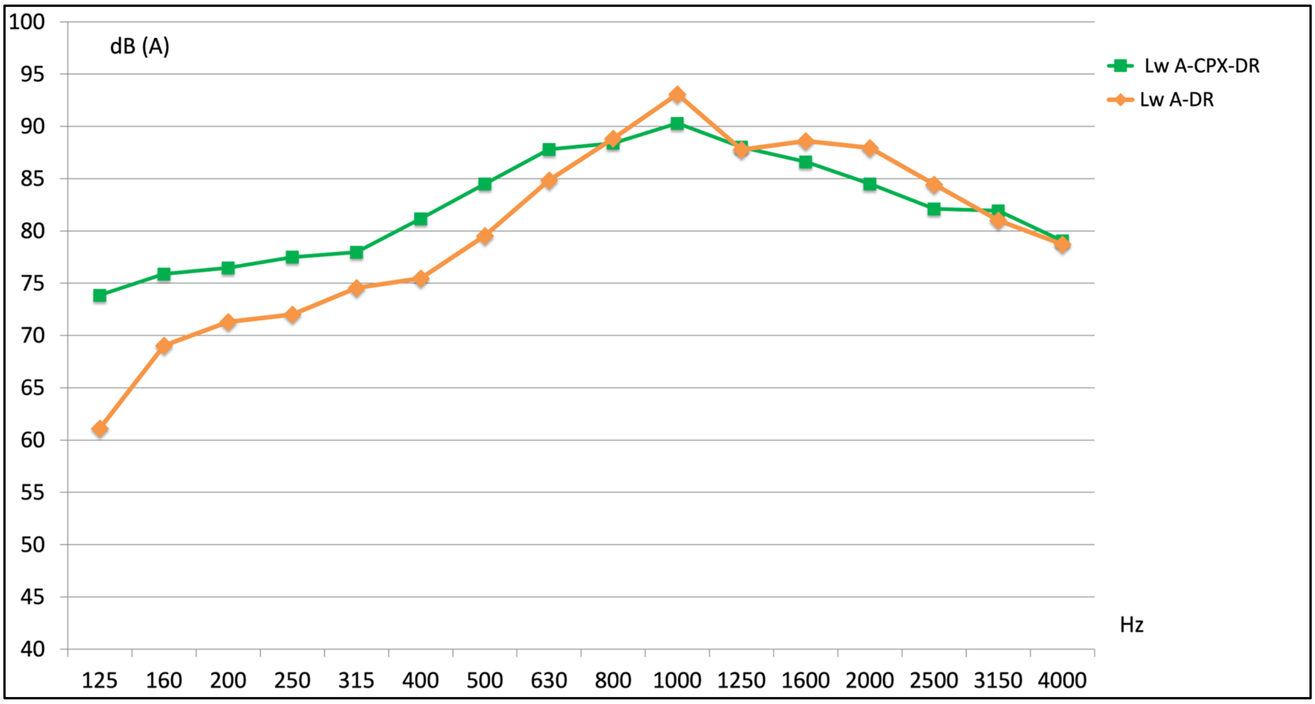

Figure 8. Sound power levels registered in both the Alternative Drum test ($L_{w\ A\text{-}DR}$) and in the Alternative CPX Drum test ($L_{w\ A\text{-}CPX\text{-}DR}$) for an INSA Turbo Sport 185/65R15 88H tyre at 80 km/h.

3.3. Coast-By Track vs. Alternative Drum and Alternative CPX Drum Tests Results Comparison

Previous sections show the CB track test results, and both the A-DR and the A-CPX-DR test results separately. Figure 9 now shows the results of the three different tests, for the same tyre, in one graph. The sound power level spectrum, $L_{w\ A\text{-}DR}$ (orange line with rhomboidal marker type), and the sound power level spectrum, $L_{w\ A\text{-}CPX\text{-}DR}$ (green line with square marker type), of a 185/65R15 88H Insa Sport tyre, measured by means of the A-DR and the A-CPX-DR test methods at 80 km/h, respectively, are shown at the top of the graph. Beneath them, there are several sound pressure level spectra obtained by different CB track tests (L_{pTrack}) for the same tyre.

When comparing all these spectra, it is important to take into account that the spectra shown in both the A-DR and the A-CPX-DR tests correspond to the SPL at a distance of 1 m, while the spectrum registered in the Coast-By track tests corresponds to the SPL at a distance of 7.5 m. This explains the difference of 20 dB between the A-DR and A-CPX-DR tests and the Coast-By track tests. For this reason, to be able to carry out a comparison, the SPL at 7.5 m has to be calculated, from the sound power level, using ISO 9613-2.

Figure 9. Sound power level spectra obtained in A-DR and A-CPX-DR tests at 80 km/h, and sound pressure level spectra obtained on Coast-By track tests.

3.4. Validation of the Alternative CPX Drum Test Methodology

The results registered using the CB track test method and the A-DR and A-CPX-DR laboratory test methods have been presented before. Note that the Coast-By track test results show the SPL at 7.5 m ($L_{p\ Track}$), while the values registered in the A-DR and A-CPX-DR tests are sound power levels, ($L_{w\ A\text{-}DR}$) and ($L_{w\ A\text{-}CPX\text{-}DR}$), obtained by the sound propagation model, described in ISO 3744, using a hemispherical measurement surface of 1 m in diameter and the CPX microphone positions, respectively, as explained in Section 2.2.2. In this section, the sound pressure levels at 7.5 m ($L_{p\ A\text{-}DR}$) and ($L_{p\ A\text{-}CPX\text{-}DR}$), are obtained from the sound power levels, ($L_{w\ A\text{-}DR}$) and ($L_{w\ A\text{-}CPX\text{-}Drum}$), according to ISO 9613-2, to validate the Alternative CPX Drum test method explained in Section 2.2.

Figure 10 shows the sound pressure level, $L_{p\ A\text{-}DR}$ (orange dotted line), calculated from $L_{w\ A\text{-}DR}$, and the sound pressure level, $L_{p\ A\text{-}CPX\text{-}DR}$ (green dashed line), calculated from $L_{w\ A\text{-}CPX\text{-}DR}$ on the Alternative Drum tests, for a 185/65R15 88H Insa Sport tyre at 80 km/h, considering the attenuation in accordance with ISO 9613-2, and the effect of four tyres instead of just one. We can see a comparison between them as well as the CB sound pressure level, $L_{p\ Track}$. Both sound pressure level spectra, $L_{p\ A\text{-}DR}$ and $L_{p\ A\text{-}CPX\text{-}DR}$, resemble the sound pressure level spectrum, $L_{p\ Track}$ (red line with circular marker type), especially in the third-octave band frequencies around 1000 Hz, where most of the sound energy is contained.

On the other hand, Table 6 shows $L_{p\ A\text{-}DR}$ and $L_{p\ A\text{-}CPX\text{-}DR}$ third-octave band sound pressure values for an Insa Turbo Sport 185/65R15 88H tyre, calculated from the sound power levels, $L_{w\ A\text{-}DR}$ and $L_{w\ A\text{-}CPX\text{-}DR}$, respectively. It also shows the difference between these values and the sound pressure values, $L_{p\ Track}$, obtained using Reg. 117.

As can be seen, important differences with the conventional CB track test results were registered in the lower frequencies for the A-CPX-DR method, and in the higher frequencies for both the Alternative Drum test methods. This behaviour is most probably caused by the different test surfaces (asphalt test track vs. smooth steel drum). However, further evaluation has demonstrated that these differences are not as important when comparing the overall sound pressure levels, L_R, which are the EU tyre type approval values.

The overall sound pressure level (L_R) can be calculated from sound pressure level spectra according to Equation (8):

$$L_R = 10 \cdot \log\left[\sum_{i=1}^{N} 10^{0.1 L'_{pi}}\right] \text{ dB} \quad (8)$$

where $L\prime_{pi}$ are the SPLs for each third-octave band.

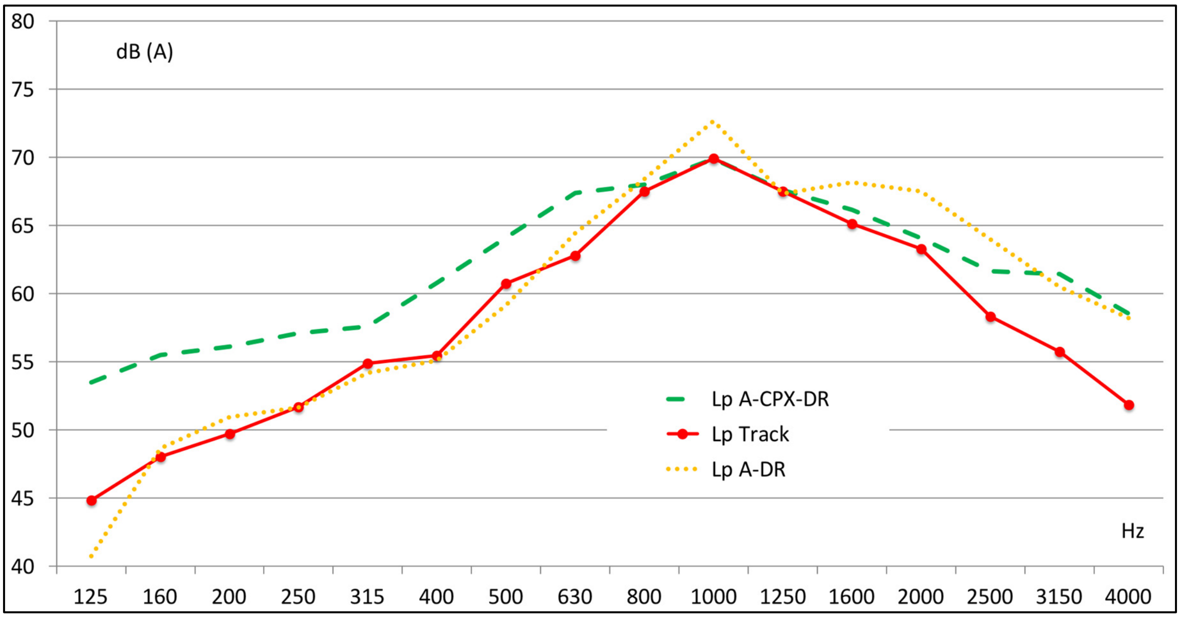

Figure 10. CB sound pressure level L_{pTrack} vs. sound pressure levels $L_{p\ A\text{-}DR}$ and $L_{p\ A\text{-}CPX\text{-}DR}$, obtained from the sound power levels $L_{w\ A\text{-}DR}$ and $L_{w\ A\text{-}CPX\text{-}DR}$ for an Insa Turbo Sport 185/65R15 88H tyre.

Table 6. Difference between $L_{p\ A\text{-}DR}$ and $L_{p\ A\text{-}CPX\text{-}DR}$, and L_{pTrack} sound pressure values.

f (Hz)	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**
$L_{p\ Track}$ (dB)	44.85	48.06	49.73	51.70	54.90	55.48	60.75	62.82
$L_{p\ A\text{-}DR}$ (dB)	40.76	48.67	50.94	51.65	54.19	55.10	59.16	64.45
$L_{p\ A\text{-}CPX\text{-}DR}$ (dB)	53.49	55.52	56.11	57.13	57.60	60.80	64.12	67.41
$L_{p\ A\text{-}DR} - L_{p\ Track}$ (dB)	−4.10	0.61	1.21	−0.05	−0.71	−0.38	−1.58	1.63
$L_{p\ A\text{-}CPX\text{-}DR} - L_{p\ Track}$ (dB)	8.64	7.47	6.38	5.43	2.70	5.32	3.37	4.59
f (Hz)	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**
$L_{p\ Track}$ (dB)	67.50	69.94	67.51	65.13	63.29	58.34	55.76	51.87
$L_{p\ A\text{-}DR}$ (dB)	68.43	72.67	67.34	68.18	67.50	64.00	60.52	58.20
$L_{p\ A\text{-}CPX\text{-}DR}$ (dB)	68.00	69.88	67.60	66.18	64.07	61.64	61.44	58.53
$L_{p\ A\text{-}DR} - L_{p\ Track}$ (dB)	0.93	2.73	−0.17	3.04	4.21	5.65	4.76	6.32
$L_{p\ A\text{-}CPX\text{-}DR} - L_{p\ Track}$ (dB)	0.50	−0.06	0.09	1.05	0.77	3.30	5.68	6.66

The overall sound pressure values are then calculated with the values shown in Figure 10 and Table 6 for both the A-DR and A-CPX-DR tests. For the 185/65R15 88H Insa Sport tyre, these values are $L_{R\_A-DR} = 77.2$ dB and $L_{R\_A-CPX-DR} = 76.4$ dB, respectively, while the overall sound pressure level, L_{R_Track}, calculated from the track tests by means of the CB track method, is $L_{R\_Track} = 75.9$ dB.

Figure 11 shows the L_{R_Track} sound pressure level results measured during the Coast-By track tests, in addition to the $L_{R\_A\text{-}DR}$ and the $L_{R\_A\text{-}CPX\text{-}DR}$ results calculated using the A-DR and the A-CPX-DR test methods. Even though the correlation between track and drum tests is not sufficient to consider equivalent methods, the results are quite similar, and when the overall sound pressure values obtained with the Drum methods are compared with the CB method, the mean values of these differences are $\overline{\Delta L}_R = 1.61$ dB for the A-DR method, and $\overline{\Delta L}_R = 0.52$ dB for the A-CPX-DR method. These differences are significantly lower than other deviations obtained using the CB track tests according to Reg. 117 [13,16]. These deviations have been classified into these factors: test track (3–9 dB), test temperature

(2 dB) and the vehicle (1.6 dB). None of them affect either the A-DR or the A-CPX-DR test methods, as both of them are carried out under laboratory-controlled conditions.

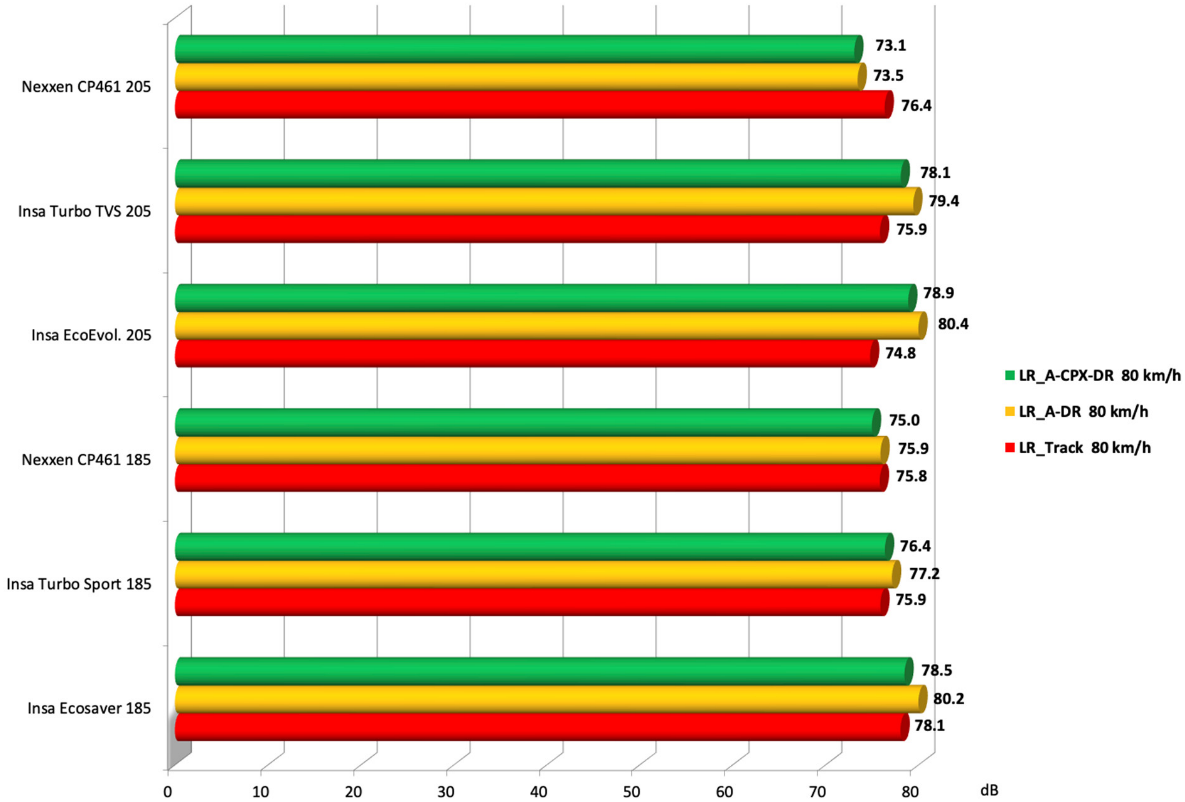

Figure 11. Comparison between type approval values obtained in the Drum and the CB track tests.

4. Discussion

The conventional Coast-By method described in Regulation 117 needs a vehicle, four tyres, a considerable amount of time and fuel, and two technicians to be carried out. Moreover, no vehicle can fit every tyre size on the market, so different vehicles need to be used depending on the tyre's size to be tested. For these reasons, the CB method is more expensive than the A-DR or the A-CPX-DR methods described in this paper.

In addition, factors such as the test vehicle, the track, background noise and temperature or wind, among others, have been demonstrated to considerably affect the repeatability and reproducibility of conventional track test methods. In fact, it has been shown that they introduce significant uncertainties in the results [7,8]. Additionally, the measured magnitude, the sound pressure level, is the most important limitation of conventional track methods, as it depends on attenuation, environmental factors or the distance between the noise source and the data acquisition system. For this reason, unless all these factors are precisely quantified and controlled, which does not occur in the CB method, it is impossible to obtain the sound power of the source.

Both the A-DR and the A-CPX-DR methods have been demonstrated to be reliable and consistent in terms of repeatability and reproducibility, and their results resemble those obtained using the conventional CB track test method. Additionally, the limitations of the acoustic test environment and background noise of the drum tyre test facilities were not only fully resolved, but even exceeded the standards of ISO 3744, which requires that results have a typical deviation lower than 1.5 dB, as established in Table 0.1 of ISO 3744. Furthermore, by using the ISO 9613-2 sound propagation model, sound pressure levels $L_{p\ A\text{-}DR}$ and $L_{p\ A\text{-}CPX\text{-}DR}$ can be calculated from the sound power levels $L_{w\ A\text{-}DR}$ and $L_{w\ A\text{-}DR}$ obtained in the Drum tests with the Alternative Drum and the Alternative CPX Drum test methods, respectively.

On the other hand, the sound pressure values $L_{R\_A\text{-}DR}$ and $L_{R\_A\text{-}CPX\text{-}DR}$, obtained in the laboratory Drum tests, are very similar to the sound pressure values, L_{R_Track}, calculated from CB track tests, which are used for type approval of tyres. Their differences have proven to be lower than the uncertainty introduced by factors such as the vehicle or the test track, especially in the A-CPX-DR method, which stands out as a more accurate, cheaper and simpler alternative test for obtaining sound pressure-approved values.

The lack of correlation between the conventional track test (CB) and the Alternative Drum tests (A-DR and A-CPX-DR) has demonstrated that results are heavily influenced by the test surface. For this reason, it is not possible to compare the type approval values of tyres which have been obtained with different methods, as rolling against a smooth steel drum is not comparable to rolling over an asphalt paved surface. The steel drum introduces completely unrealistic conditions of interaction between the tyre tread and the road surface. In order to improve the correlation between the track and drum tests, solutions such as mounting replica road surface sections on the drum have been considered. However, the effect of centrifugal forces or the joints between sections causes significant parasitic noises, which is an important—but not the only—problem caused by this approach. Moreover, small differences in the characteristics of the surface that occur on the measurement sections covered with the ISO surface cause measurable differences in tyre noise. For this reason, the study of tyre noise using smooth steel drums using the presented Alternative Drum test methods and considering sound power levels instead of sound pressure levels, which has not yet been done, should not be rejected.

The test environment and the fundamental parameters of the Alternative CPX Drum test have been shown to be more controllable than those of the CB track test. In addition, the A-CPX-DR test methodology has been validated and demonstrated to be more accurate and repeatable and to have lower uncertainty than Reg. 117. Moreover, the information provided by the A-CPX-DR method is more accurate, as the noise spectrum along with the overall sound pressure level is calculated, unlike the CB method, where only L_R is measured. For these reasons, the Alternative CPX Drum test methodology could be considered as an alternative simpler option, but in no way comparable or equivalent, to the track method established in Regulation 117 for type approval of tyres.

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