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The influence of tyres on the use of the CPX method for evaluating the effectiveness of a noise mitigation action based on low-noise road surfaces

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ABSTRACT

The usage of low-noise road surface can be an important and effective noise mitigation action and, in many cases, it might represent the only viable solution. After the laying of a low-noise road surface, it is necessary to verify if the planned objectives have been actually obtained: the Close Proximity Method (CPX) could be a possible method to achieve this result.

The current release of the ISO 11819 draft regarding CPX redirects to a future third part for all details about the reference tyre to be used, while the previous one gave indications on dimensions, kind of tread pattern and maintenance conditions. As well known, tyre dimensions and tread pattern are the main sources of variability of rolling noise. Even though many tyres available on the market comply with all ISO requirements, the choice of a brand or a model rather than another one could nevertheless influence results of measurements.

In this work, results obtained in several measurement sessions, repeated using different tyres, are compared, aiming to analyse the influence of the tyre choice in assessing the acoustic performance of a low-noise road surface. Limitations and advantages of the CPX method in regards to the evaluation of the effectiveness of a noise mitigation action are reported, and new perspectives are suggested, in order to improve the relationship with the noise level reduction at the receiver.

1. Introduction

Noise pavement classification is an open issue: while some EU countries (Kragh et al., 2012; Anfosso-Lédée and Leroux, 2012) have their own method of classification, at present there is not an international standard based on common definitions. At CEN level, a standard is currently on discussion, while JRC of EU Commission has published the Revision of Green Public Procurement Criteria for Road construction; this review contains criteria to classify low-noise road surfaces (Garbarino et al., 2016). Some points have yet to be defined, i.e. standard denomination of pavements, criteria to describe the physical characteristics of the surface, the relationship between physical parameters and noise and, finally, a set of mea-

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surement methods to be applied. The last point requires an evaluation of the feasibility based on reproducibility and repeatability, practicability, significance, robustness, and cost.

Another important matter is evaluating the effectiveness of a specific noise mitigation action based on a low-noise road surface, which follows different rules from those used for noise pavement classification. Firstly, as already stated, the effect of the mitigation action must be evaluated at the receiver. Secondly, a road surface, in the framework of mitigation actions, can be several kilometers long and, therefore, spatial homogeneity of the installation must be taken into account. Pass-by results (ISO, 11819-1, 1997) could be a proxy of the receiver exposure, however, this method is only capable of describing a sketch of road a few meters long. In order to evaluate the acoustic performances along the whole installation, it is necessary to shift to the CPX method (ISO/DIS, 11819-2, 2015) which, combined with pass-by measurements, is recognised to be a suitable tool for both noise pavement classification and noise mitigation action assessment. Nowadays, the recognised models (Beckenbauer et al., 2008) can predict pass-by noise for different road surfaces, using tyre parameters as input. Anyway, the correlation between CPX and pass-by results (Anfosso-Lédée, 2004) is still subject of research and, for example, combining both methods into a harmonised pavement noise emission characterisation method is a priority of the ROSANNE Project (ROSANNE).

The Region of Tuscany has led the way in Italy, adopting the CPX method as the official test required to assess the efficacy of a low-noise road surface when used as noise mitigation action, establishing that the acoustic performances must be monitored for at least three years after the laying, whilst the JRC GPP requires a 5 years long monitoring. Requirements adopted in Tuscany derive from the LEOPOLDO project (Licitra et al., 2015a), which has led to guidelines containing criteria on materials and technologies useful for municipalities that need to plan noise mitigation actions based on the usage of low-noise road surfaces. Within the project, a modified measurement protocol of the CPX method was developed (Licitra et al., 2014).

As far as the tyre to be used in the CPX method is concerned, it is known that, for a certain road surface, tyre dimensions are the main source of amplitude variability for rolling noise (Phillips and Abbott, 2001), while tread pattern has a clear influence in the emission spectrum (Sandberg and Ejsmont, 2002). Moreover, recently some studies have been carried out to analyse the influence of tyre hardness (Ho et al., 2013; Bühlmann et al., 2013; Sandberg and Ejsmont, 2007). Thus, the characteristics of the tyre represent a critical issue, and, unfortunately, every specific combination of tyre and road surface has a clear influence on results (Berge et al., 2015), up to a level that the tyre noise labelling (European Parliament Regulation, 2009) cannot be considered a reliable indicator (Swieczko-Zurek et al., 2014).

In the previous draft of the ISO 11819-2 (ISO/CD, 11819-2, 2006) tyre dimensions, kind of tread pattern and maintenance conditions were prescribed, while the current release (ISO/DIS, 11819-2, 2015) redirects to the ISO/TS 11819-3 (ISO/TS, 11819-3, 2016) for all details about reference tyres. It is known that the ISO committee which is writing the 11819-3, suggests the SRTT and the Supervan AV4 (Berge, 2013).

Establishing a reference tyre has the clear advantage of improving the reliability of comparison between results obtained by different laboratories. Moreover, the usage of a reference tyre is the only way to perform the classification of the type of pavement, also known as pavement acoustic labelling (Anfosso-Lédée et al., 2016). On the other hand, requiring the use of a particular reference tyre, as in case of SRTT, would mean losing most results obtained by several laboratories in the past years. Indeed, whilst waiting for the ISO/CD 11819-3, several laboratories have used their own "reference tyre", choosing among many models, marketed by several brands, which all comply with all requirements prescribed by the previous draft of the ISO 11819-2. Besides, using only the reference tyre would mean also reducing the possibility of the CPX data to be representative of the noise produced by the real light vehicle traffic, especially in European countries where car fleets use smaller tyres.

The aim of this work is to investigate the influence of the tyre choice when the CPX method is extended for the evaluation of the effectiveness of a low-noise road surface laid in order to provide noise mitigation action. The study is carried out in the framework of both rubberised surfaces research (Licitra et al., 2015b) and LEOPOLDO project. CPX data obtained using different tyres, in accordance to the previous ISO 11819-2 draft, have been here collected and results have been compared.

2. Method

2.1. Measurement protocol

In this paper, the modified protocol based on the CPX method described in (Licitra et al., 2014, 2015a) is used. Results are shown in terms of tyre/road noise levels, without strictly referring to the actual CPX indexes, but for the sake of simplicity they are hereafter named as L_{CPX} values.

The set-up is based on the measurement system mounted on a self-powered vehicle and the modified protocol leads to the following main improvements: the analysis is based on the spatial resolution of a "segment" defined as three times the tyre circumference, approximately 5.9 m; during the measurement session, acquisitions over the tested surfaces are repeated several times, varying the vehicle speed. Then, a minimum chi-squared based iterative algorithm is used for fitting sound levels and speed data, for each segment and for each third-octave band level, in order to compute the L_{CPX} values at the reference speeds using the right speed coefficient; finally, the mean value of the segment results, named L_{CPX} in the following, is used to characterise the whole road surface installation.

2.2. Measurement uncertainty and spatial variability

The uncertainty related to the result, i.e. the averaged L_{CPX}, derives from three distinct sources of error or data variability. Firstly, segment results are obtained by means of the fitting process and then they are provided with a related uncertainty due to data dispersion around the fit. Data dispersion around the fit is mainly due to the measurement process, thus it is a clearly random source of error and it is the "measurement uncertainty".

To obtain the uncertainty related to the mean value L_{CPX} computed along the whole installation, the spatial homogeneity of the installation, i.e. the data dispersion around the mean value by means the standard deviation, must be taken into account. Spatial homogeneity is a specific characteristic of the surveyed installation, not actually a source of variability for the measurement method. Then, the deriving part of uncertainty is a description of the precision of the mean value and it cannot be neglected when two road surfaces are compared.

All in all, it must be noticed that, in most cases, the measurement uncertainty is one order of magnitude lower than the standard deviation due to the spatial inhomogeneity of the road surfaces. Nevertheless, since both contribute to the uncertainty related to the $L_{CPX,}$ in this work both are considered by their quadratic sum.

The last source of data variability derives from "several factors and processes, which cause and nature of these disturbances are either known, but randomly distributed in an uncontrollable way, or are of a systematic nature, but affect the result in an unpredictable way" (as declared in Annex K of the ISO 11819-2). Thus, during a single measurement session, the effects due to these sources of error, well described in the ISO, affect systematically the measures. Anyway, their influence must be considered of random nature, when results obtained in different measurement sessions, carried out in different days and/or with different set-up or instrumental chains, are compared, and it leads to a combined standard uncertainty of 0.5 dB, with k = 1 chosen coverage factor.

In the following, only the uncertainties due to the first two sources of variability are shown, since the third source is the same for all values and showing it would not provide any useful additional information.

2.3. Differential criterion

In case of a low-noise road surface laid as mitigation action, according to the modified procedure, the data acquisition during the measurement session must be extended over a second road surface, chosen as "reference". In this way, the measurement conditions affect systematically both road surfaces, and the influence of the systematic sources of error are minimised. In particular, this means that the acoustic performances of a low-noise road surface will be assessed comparatively to a reference one, typically a DAC 0/12 (Jonasson, 2004), through the "L_{CPX} differential values" (as named in the following).

3. Results

3.1. Analysis of L_{CPX} values

Measurements have been carried out on three sites of the LEOPOLDO project, using four different tyres, all of them compliant with the reference type B (185/60 R15) of the second last release of the ISO 11819-2 (ISO/CD, 11819-2, 2006). All tyres were almost new, without any defects and with tread rubber hardness similar and about 63–64 Shore-A. In all tyres, tread pattern has a synchronous randomisation, the two sides almost symmetric and bi-directional (Sandberg and Ejsmont, 2002), as shown in Fig. 1. Model, brand and noise class are reported in Table 1.

For each site, measurements have been carried out on the low-noise road surface (also "LN" in the following) and on the "reference" one used in the LEOPOLDO project. In two sites, the reference surface is part of the pre-existing road surface, laid before the low-noise one, whereas in case of the third site the two road surfaces are coeval. The comparison between the three sites is out of the aim of this work. Details about road surfaces, reported in Table 2, are not relevant to evaluate differences due to tyres, which have been tested on the same road surfaces.

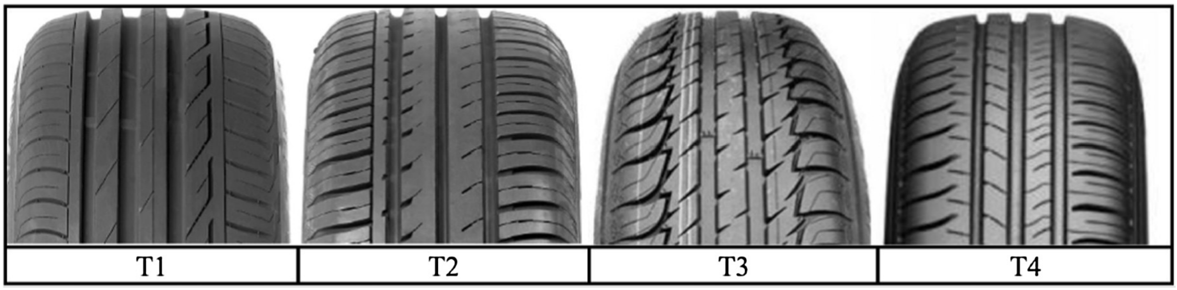

Fig. 1. Tread patterns of the tyres used in this work.

Table 1
Details of the tyres used in this work and their tread pattern.

Id	Brand	Model	Noise class
T1	Bridgestone	Turanza T001	2 (71 dB)
T2	Continental	EcoContact 3	2 (69 dB)
T3	Kebler	Dynaxer HP3	2 (69 dB)
T4	Michelin	Energy XSE	2 (68 dB)

Table 2
Road and related reference surfaces surveyed in each site.

Site	Low-noise	Reference
S1	ISO10844 optimized texture dense grade 0/8	DAC 0/12 pre-existing
S2	Dense grade 0/6 with expanded clay	DAC 0/12 pre-existing
S3	Asphalt rubber (wet process) gap grade 0/8	DAC 0/12 coeval

Table 3
L_{CPX} levels averaged on the installations of both test road surface and reference one per each site.

Site	Surface	$L_{CPX,T1}$ [dB(A)]	$L_{CPX,T2}$ [dB(A)]	$L_{CPX,T3}$ [dB(A)]	$L_{CPX,T4}$ [dB(A)]
S1	LN road surface	87.5 ± 1.3	88.3 ± 1.2	90.1 ± 1.1	88.4 ± 1.2
	Ref road surface	91.2 ± 0.3	91.6 ± 0.5	93.3 ± 0.4	91.8 ± 0.3
S2	LN road surface	89.6 ± 0.3	89.2 ± 0.3	91.4 ± 0.3	89.8 ± 0.3
	Ref road surface	92.5 ± 0.6	91.7 ± 0.8	94.2 ± 0.6	92.5 ± 0.6
S3	LN road surface	89.6 ± 0.4	88.6 ± 0.5	91.1 ± 0.4	89.1 ± 0.4
	Ref road surface	91.9 ± 0.7	91.2 ± 0.7	93.7 ± 0.7	91.4 ± 0.5

For each site, absolute L_{CPX} levels, averaged on the installations of both test road surface and reference one, are reported in Table 3. All values are calculated at the reference speed $v_0 = 50$ km/h, corrected for air temperature (ISO/TS, 11819-3, 2016) and provided with the 95% level of confidence (i.e. with a coverage factor k = 2).

The L_{CPX} levels reported in Table 3 are plotted in Fig. 2, grouped by road surfaces.

In each site, differences of about 2–3 dB(A) are detected among tyres, without any relationship with the noise label reported in Table 1. In particular, T3 always shows higher levels.

Tread pattern can generate differences both in frequency distribution and in total sound energy. In order to evaluate the influence of the tread pattern in the frequency distribution, Fig. 3 compares noise spectra with the normalised ones, for each low-noise road surface. A normalised spectrum possesses a total energy always equal to 0 dB and is therefore more useful

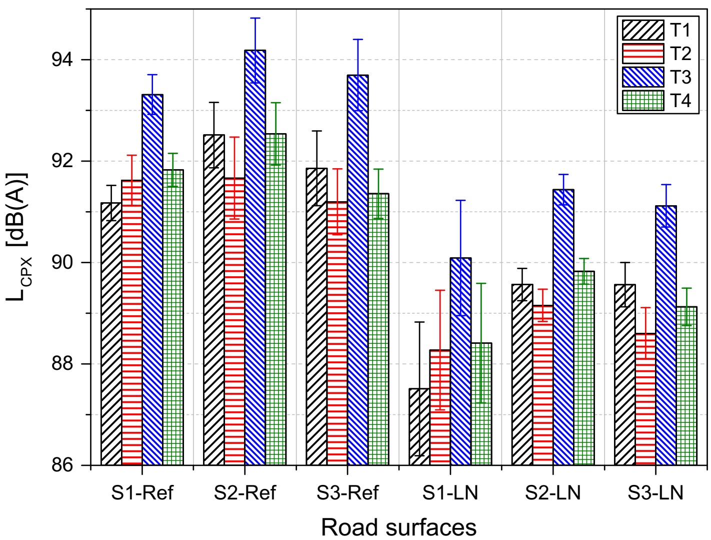

Fig. 2. L_{CPX} levels averaged on the installations of every surface grouped by road surfaces.

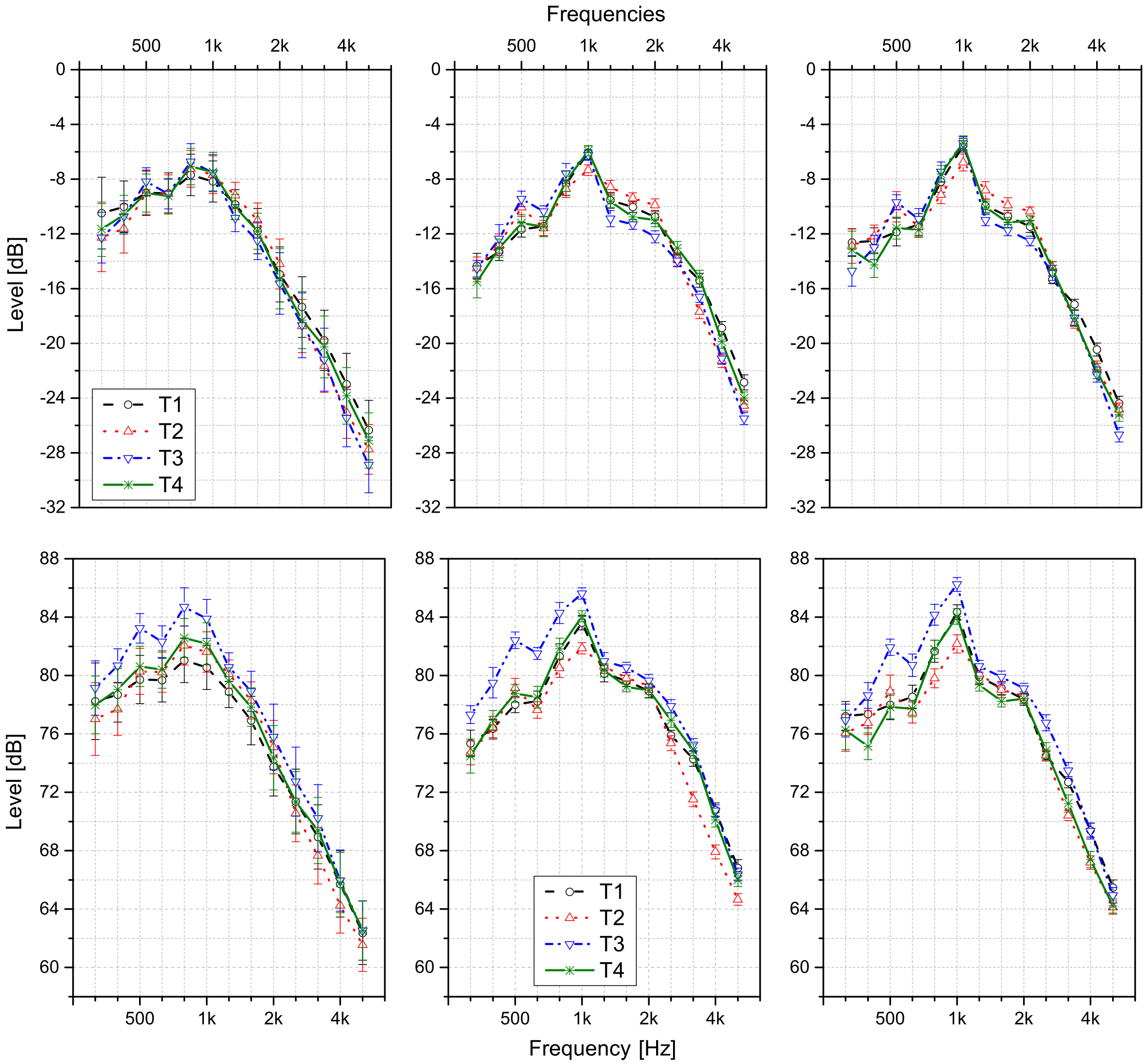

Fig. 3. Comparison between noise spectra (above) and normalised ones (below) obtained on the low-noise road surface in each site, depending on tyres.

when comparing the specific frequency behaviours of spectra containing different sound energy, highlighting the relative sound pressure levels of each band. Analysing Fig. 3, it can be noticed that the frequency distribution is slightly different among tyres, but not enough to justify the differences among absolute A-weighted broadband levels, since T3 shows higher band levels for almost all frequencies, probably due to the rubber compound of the tyre.

Carrying on the analysis of results shown in Fig. 2, it can be noticed that differences between absolute broadband levels obtained using two different tyres are not always constant among road surfaces. This phenomenon is easier to see in Fig. 4, where differences computed for all couples of tyres for each road surface are shown. The differences plotted in Figs. 4 and 5 are computed as arithmetic subtraction of the levels obtained with tyres, as explained in Eq. (1)

$$t_i - t_j = L_{CPX_{Ti}} - L_{CPX_{Tj}} \tag{1}$$

In the case of the couple T1 and T2 and in the case of the couple T1 and T4, differences vary significantly among road surfaces. Data uncertainties shown in Fig. 4 derive from the propagation of uncertainties related to the absolute values and they are provided with the 95% level of confidence.

Results shown in Fig. 4 can be computed as the differences of the mean values of data obtained for each tyre along the two road surfaces or averaging the differences between data obtained per each segment using two tyres. Even though both averaging calculations are weighted with the related uncertainty, results do not change significantly.

Data shown in Figs. 2 and 4 have two outcomes: first of all, the influence of each specific tyre/road configuration on noise levels is confirmed, and no clear relationship between tyres alone and levels recorded is evident. As an example, T1 and T2

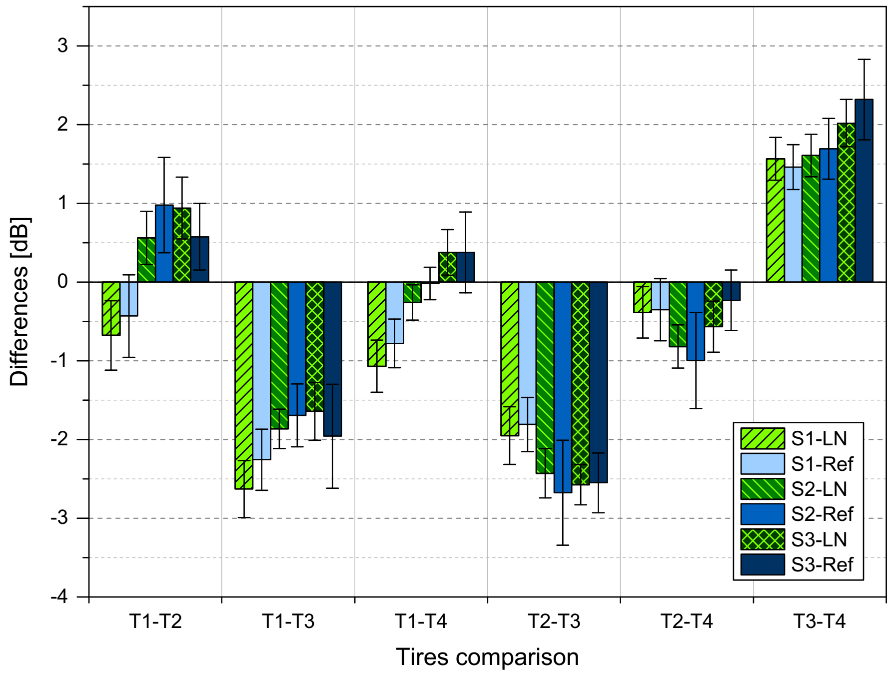

Fig. 4. Differences between tyres, calculated for every couple and for each road surface.

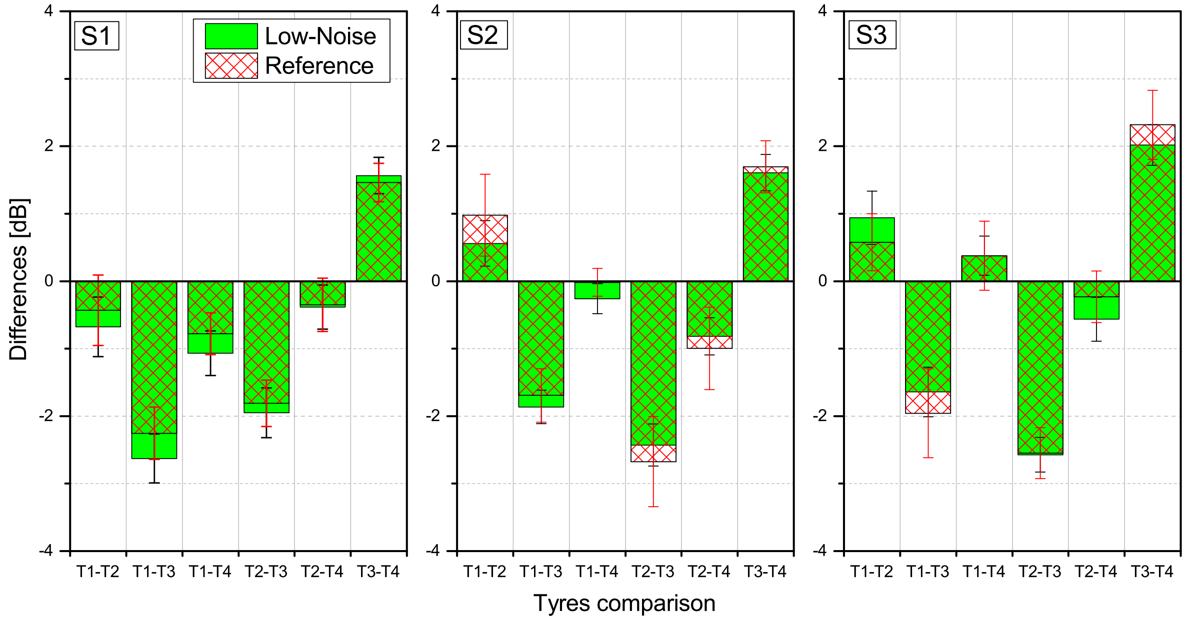

Fig. 5. Differences between tyres, calculated for every couple, grouped by road surfaces.

show different behaviours moving from S1-LN to S2-LN surfaces; secondly, as expected, the influence of the third source of data variability, above described, is minimised when the comparison is carried out between two road surfaces surveyed in the same measurement session. As a matter of fact, differences computed for all couples of tyres show a better agreement for low-noise and reference surfaces of the same site. This is better highlighted in Fig. 5, where the same data reported in Fig. 4 are grouped by site.

This is a confirmation of the high influence of the measurement conditions on tyre/road noise measurements, which will be minimised applying the differential criterion.

Since absolute values are influenced by measurement conditions and specific tyre/road configuration, therefore the CPX results obtained simply using a generic tyre compliant with the second last release of ISO 11819-2 (ISO/CD, 11819-2, 2006), cannot be a suitable indicator to describe tyre/road noise emission due to the actual car fleet.

The role of the uncertainty related to results is also crucial in the assessment of acoustic performances of the specific laid pavement. As explained above, the main part of the uncertainty related to the result is caused by spatial distribution of sound levels, which is mainly due to the road surface inhomogeneity caused by physical characteristics, i.e. texture profile. Changing the tyre adopted does not cause any significant differences in spatial distribution of sound levels, as shown in Fig. 6 in case of the site 1.

Moreover, in Fig. 7, the uncertainties related to the L_{CPX} mean values are shown for each tyre and each road surface. It can be noticed that the uncertainties vary significantly, showing differences among road surfaces (Fig. 7a), however turning out to be quite constant among tyres (Fig. 7b).

Thus, the third result that can be obtained from this analysis is that the spatial homogeneity can be described by means of L_{CPX} uncertainty without necessarily using the reference tyres as required in the Annex H of the ISO 11819-2.

3.2. Analysis of L_{CPX} differential values

Considering the low-noise road surfaces laid as mitigation action, the differential criterion can be applied. The differential values, obtained computing the differences between the low noise road surface levels and the reference ones for all sites per each tyre, are reported in Fig. 8. The differential criterion describes the acoustic performance of low-noise road surfaces better than the analysis of the L_{CPX} absolute values, since the differential values computed from absolute values measured in the same measurement sessions are less influenced by the measurement conditions than those computed using absolute values relative to different measurement sessions. Moreover, in this way the influence of specific spectral effects due to the tyre tread pattern are also avoided.

Anyway, the differential values reported in Fig. 8 turn out to be equal among tyres, only considering the related uncertainties, calculated propagating the ones related to the absolute levels.

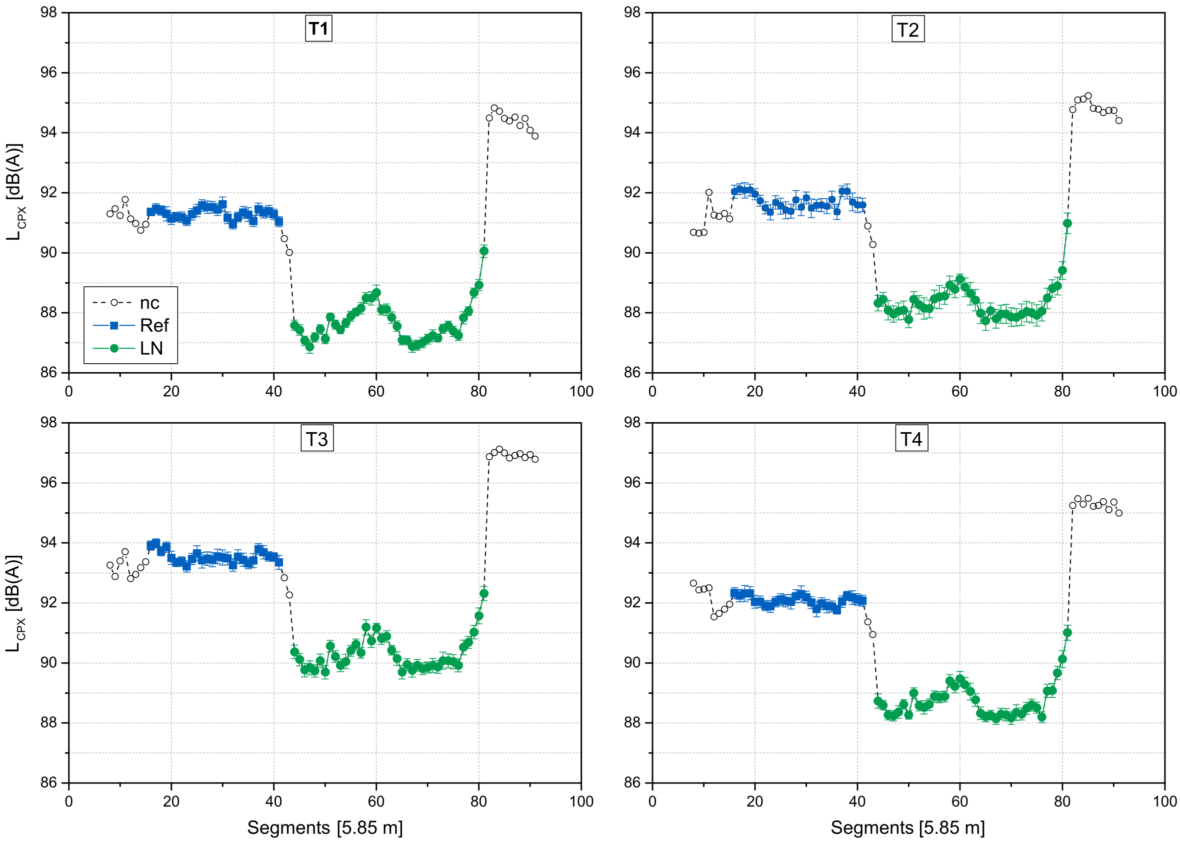

Fig. 6. Spatial curve trend of sound levels obtained in case of the site 1 using the four tyres. The blue line shows the Reference road surface, in red the low-noise one. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

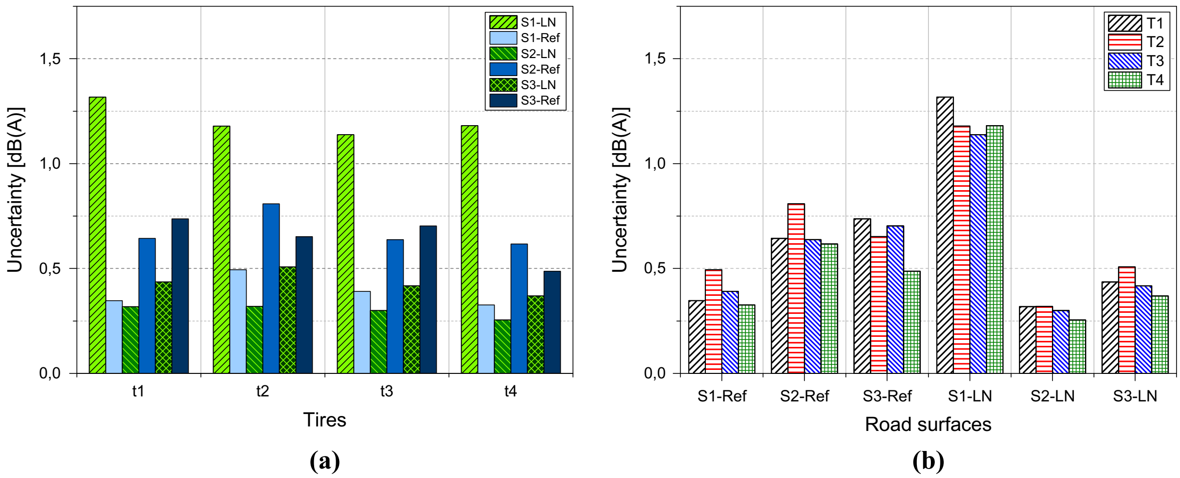

Fig. 7. Uncertainties related to the LCPX mean values, for each tyre and each pavement. On the right (a), uncertainties are grouped by tyre, on the left by road surfaces (b).

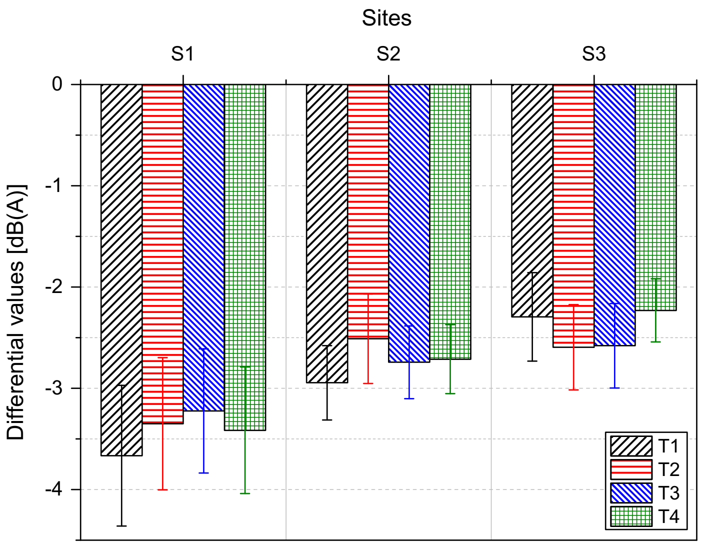

Fig. 8. L_{CPX} differential values obtained as difference of low-noise road surface results and reference ones for all sites per each tyre.

Since providing a mean value without the related uncertainty would obviously have no significance, as it is a part not negligible of the result itself and must be declared, in order to be able to provide an answer to whether the differential values are influenced by tyres or no, further analysis can be carried out, bearing in mind the final purpose of the assessment of mitigation actions.

When planning a noise mitigation action, public administration needs to know the reduction of noise level at the receiver that the installation of the low noise road will bring about. Noise level reduction has necessarily to be defined in comparison with another road surface. Following the point of view of noise pavement classification and, therefore, the idea of an absolute reference road surface, differential values can be computed for each tyre and for the three low-noise road surfaces comparing them to the same reference one. The reference road surfaces used in this work comply with the ISO annex L requests. Among them the S1-ref one shows the lowest related uncertainty and, reminding that comparison between the three sites is out of the aim of this work, it can be chosen to apply the differential criterion. Results are reported in Fig. 9.

In case of low-noise road surfaces on sites S2 and S3, related uncertainties are lower and differential values differ among tyres in some cases. In this analysis, the error due to the influence of the measurement conditions should be considered and the combined uncertainty of 1.0 dB(A) (95% coverage probability) should also be included. In most cases, this would lead to consider differential values not dependent on tyres, but information about the effectiveness of the mitigation action would be too inaccurate, and the CPX results would not be useful.

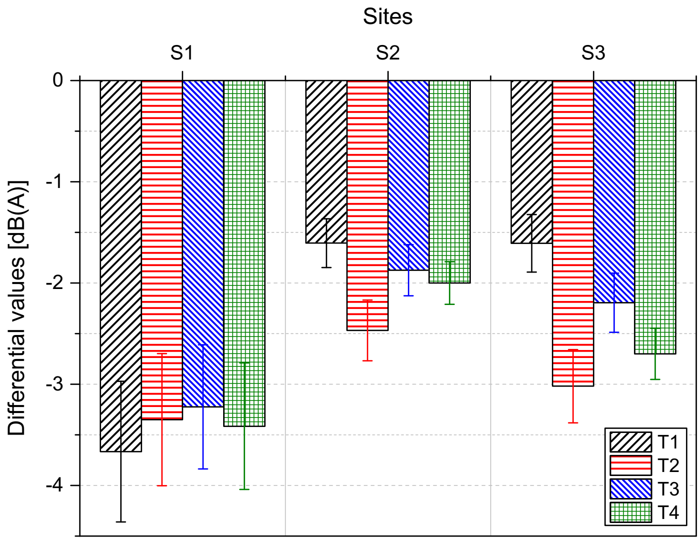

Fig. 9. Differential values obtained for the three low-noise road surface, using the S1-Ref as common reference.

4. CPX and noise mitigation action

As explained above, for the planning of a noise mitigation action, public administration needs to know how much noise level reduction at the receivers can be obtained thanks to the laying of a low noise road surface. Furthermore, the second relevant challenge is to correlate a measure of the source power, i.e. the tyre/road interaction noise, with roadside measurements (ROSANNE), in order to determine the correct sound power to be used for noise mapping. The lowering of receivers' noise levels and the decreasing of the source power provided by the low noise road surface need both to be quantified considering a differential value using a reference road surface.

A choice could be the usage of a fixed value for a reference road surface, i.e. following the idea of a pavement classification based on noise. This would lead to an increase of the related uncertainty, weakening the usefulness of the results. Another possibility is to carry out measurements on both low-noise and reference road surfaces, which must be laid in the same site and surveyed during the same session. This permits to minimise the influence of measurement conditions.

In this case, there are two possible sub-choices: the term of comparison can be provided by a coeval most common road surface used in the area or by the pre-existing one. In order to simplify and standardise the planning procedures of public administrations, the comparison with the previous state should be avoided. In fact, the differential evaluation could show high variations, due to the type and wearing condition of the pre-existing pavement. Thus, results obtained by means of the same low-noise road surface laid in two sites could be not fully comparable.

Another shortcoming of the usage of a pre-existing pavement as reference is that the measured improvement is due both to the acoustic performances of the low noise road pavement and the pavement renewal itself, with no possibility to distinguish the two contributes.

On the other hand, choosing a coeval most common road surface as reference describes more accurately the actual benefit provided by the low noise road pavement. Unfortunately, this choice is not always viable since not all low noise pavements are laid with a coeval adjacent reference.

A good balance among all the possibilities analysed above could be reached by planning the installation of a reference road surface, handled by the public authority in charge to regulate limits and measurement methods for the acoustical characterisation of the road surfaces. The most common road surface used in the area should be used for the reference installation, and influence of temperature, ageing or other conditions should be investigated in detail. In this way, every result obtained for a tested road surface could be compared to those obtained for the reference one with same conditions, as temperature and age. In addition, if a comparison with the pre-existing state were available, it would be possible to know the improvement due to the pavement renewal.

Regardless of previous observations, the extension of the CPX method to the evaluation of the effectiveness of a noise mitigation action cannot overlook the influence of the tyre.

Considering that the road noise depends on the actual car fleet, in order to obtain a more representative CPX result, it would be necessary to take into account an average data obtained using several common tyres available in the market. In this way, the relationship between pass-by and CPX results could also be improved, the noise mitigation action effectiveness could be estimated directly from CPX measurements and, in general terms, a better information could be derived for the noise mapping procedure. Further research would be necessary to evaluate the feasibility of the usage of more than one tyre in the application of the CPX method. Anyway, the suggested use of the SRTT tyre in the ISO/TS 11819-3 could lead to CPX result as suitable indicator for the car fleet and some results of the ROSANNE project are promising (Anfosso-Lédée et al., 2016).

5. Conclusions

Influence of tyre, mainly of its dimensions and tread pattern, on tyre/road noise levels depending on the road surface characteristics is still subject of research. Pass-by methods applied for acoustical characterisation of road surfaces take into account the actual car fleet, however they are useful in the description of only short sketches of roads, while every type of road surface can suffer troubles during installation, at all stages of mixing and laying process, due to lack of care or experience. Instead, CPX measurements allow to highlight the spatial homogeneity of the installation, directly related to the quality of the laying work, but results depend on specific tyre/road configuration. Aiming to extend the CPX method to the evaluation of the effectiveness of a noise mitigation action based on the usage of a low-noise road surface, the choice of the tyre represents an unavoidable problem. For this purpose, the measurements presented in this paper have been carried out on several sites with different tyres. Results show that acoustic performances of road surfaces cannot be correctly evaluated using just one kind of tyre. This is true unless a differential criterion is applied, using as term of comparison a reference road surface laid on the same site, which allows to monitor the temporal trend of the acoustic performance of the road.

Moreover, the real effectiveness of noise mitigation action at the receiver does not show a direct relationship with the CPX measurements carried out with just one type of tyre, since results depend on it.

Further studies will be necessary to analyse the advantages of the usage of several tyres in a new procedure, in order to correlate CPX results with real reduction of noise level at the receiver.

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