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Durability and variability of the acoustical performance of rubberized road surfaces

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ABSTRACT

The use of road surfaces with low noise emission characteristics is one of the actions mostly applied all over the world to decrease the number of road traffic noise annoyed people. Since many Italian roads are going to be paved with such surfaces, the LEOPOLDO project (funded by the Tuscany Region and the Italian Ministry of Transportation) was planned to check the efficacy in time of this action. Among all solutions, rubberized road surface is one of the most applied in USA, Canada, Europe and Asia. This paper describes results obtained by monitoring four rubberized surfaces one year after the laying and by evaluating the time stability of LEOPOLDO one by means of the Close Proximity method (CPX). All surfaces here analyzed are laid in real scenarios, so the actual efficacy of this action is evaluated. The results on the LEOPOLDO surface show spatial homogeneity, a good time stability and a significant noise emission reduction. Instead, analysis of the four rubberized surfaces shows variability in the results, probably due to the pavement installation quality, as supported by the data. Thus, the rubberized road surface looks to be a very efficient mitigation technology, providing the installation have been carried out with care and proficiency.

1. Introduction

Transportation noise is an environmental stressor that causes sleep disturbance and annoyance. The latter is the most frequently ascertained effect of noise in people living in urban areas. The reduction of the urban road traffic noise pollution and of the population noise exposure becomes mandatory. The use of road surfaces with low noise emission characteristics is one of the actions mostly applied all over the world to achieve this goal.

Several projects co-funded by European Union (SILVIA [1], QCITY [2], SILENCE [3]) proposed and studied many actions based on low emission road surfaces. Among them, a solution is provided by pavements incorporating rubber, which often have the great environmental benefit of contributing in the scrap tires recycling.

There are mainly two different applications of rubber in pavements: porous elastic road surfaces (PERS) and rubberized surfaces. While the former technique uses rubber as the main component, in the latter rubber is mixed with common asphalt components. A PERS [4,5] is defined as a mix of air void content (20–40% in volume) and of rubber (till 90% in weight). Typically, it consists of an aggregate of rubber granules or fibers, sometimes supplemented by sand, stones or other friction-enhancing additives, bound together with a binder of bitumen or polyurethane. In 1983 Nilsson [6] firstly introduced them as a low-noise pavement technique. In fact, this technology provides a very elastic surface, lowering vibrations excited by tire rolling.

Rubberized surface technology uses crumb rubber as a modifier in asphalt mixtures in order to improve the properties of binder by reducing its inherent temperature susceptibility, as described in [4,7], in several ASTM documents (see [8] and successive editions). Moreover, the addition of crumb rubber into the binder increases its elasticity and resilience, improving the durability and the resistance to fatigue.

Rubber can be incorporated into asphalt paving mixes through two main different methods, the "wet process" and the "dry process".

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The wet process rubberized surfaces, historically named "Asphalt–Rubber" pavements, have been successfully used for over 35 years in many states in the USA and all over the world. This technology is defined by ASTM [8] as: "A blend of asphalt binder, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt binder sufficiently to cause swelling of the rubber particles". So, in the wet process, the crumb rubber is blended with asphalt cement, usually in the range of 18–25%, before the binder is added to the aggregate. During the interaction with asphalt binder, the crumb absorbs a portion of the aromatic oils in the asphalt binder, swelling particles and increasing the binder viscosity and stiffness. This reaction is influenced by many factors, among which the main one is the duration of the blending at the prescribed temperature.

The dry process for rubberized surfaces, was originally developed in the late 1960s in Sweden. In this process, rubber is blended to the aggregate, usually in the range of 1–3%, before the addition of the asphalt cement. Rubber can be used in both coarse and fine crumb, to match aggregate grading and to achieve an improved binder modification, and it may need a pre-treatment with a catalyst to achieve optimum particles swelling. Wide use of dry process for rubberized surfaces began in the late 1980s in USA and in many European sites since the year 2000.

The acoustic performances of solutions incorporating rubber have been studied since the beginning. In particular, acoustics performances of PERS were firstly studied in 1980s: for example, Nilsson and Zetterling [9] evaluated the noise reduction at roadsides in about 10 dB(A). Anyway, in the 1990s PERS was still at a stage of experiment, with an interesting potential in reducing traffic noise according to Sandberg studies [10]. Afterwards, PERS have been widely studied in Japan, finding that the effects on roadside noise reduction were superior to those of drainage asphalt surfaces [11].

After the world wide spreading of the rubberized surface technology in the 1990s, several studies started out also on this technology. The earlier studies, using the Close Proximity method (CPX) [12] on both gap graded and open graded surfaces, suggested that the rubberized ones provide more favorable conditions for noise reduction than those of similar pavements not using crumb rubber (e.g. SMA) and porous asphalt concrete. Moreover, the advantage might become greater with time and age of the pavements [13]. Recent European studies showed that there were noise reductions of about 2 dB(A) [14], whereas a study in Portugal [15] tested three road sections with open and gap-graded mixtures, two of them with rubberized surfaces, in order to monitor the tire-road noise within a time span of three years. A Canadian study [16] using the CPX method found a difference of 5.4 dB(A) between the quietest and nosiest surfaces. Concerning roadside noise measurements, some studies were carried out in Portugal and an abatement in A-weighted levels up to 8–10 dB was observed. Freitas and Antunes [17] analyzed rubberized surface acoustic behavior using Statistical Pass By method (SPB) [18]. In some studies, the sound attenuation were monitored over time, showing that the roadside noise level due to rubberized surfaces increases less than in case of conventional pavements. [19–21].

In the last few years, an increasing number of roads are going to be paved in Italy using the rubberized surfaces, with both wet and dry process, and some specific studies were performed in order to check the efficacy of this solution as a mitigation action. In particular, in the recent past, ARPAT (Environmental Protection Agency of Tuscany Region, in Italy) acoustically characterized four different experimental rubberized surfaces, mainly using the CPX. One of them have been laid within the LEOPOLDO project [22], developed in Tuscany since 2006 by Tuscany Region and its provinces: this project aimed to study the acoustical characteristics of some experimental surfaces, laid on stretches about 200 m long of extra-urban main roads. Acoustical performances had to be monitored evaluating the tire/road noise emission for several years, because a surface used to mitigate noise pollution should have also a lasting efficacy.

This paper describes the results obtained after one year from the laying, comparing all the four rubberized surfaces considered. Besides, the time-stability of the LEOPOLDO project one was evaluated using both CPX and SPB measurement methods over 4 years. The aim is to figure out the strengths and the weakness of the rubberized surfaces used as acoustic mitigation action in real scenarios.

2. Measurements methods

2.1. The Close Proximity (CPX) method

The CPX method uses two microphones placed close to the tire to measure the tire-road noise as far as it dominates all other noise sources, such as the power unit. In this paper, an adapted measurement and data post-processing methodology, based on the CPX method, is used. This adapted methodology is based on ISO/CD 11819-2 3rd release (2000) and is presented in another paper [23]. The analysis here presented improves the previously published one [23], adopting some features presented in the 2011 release of the norm, until now subjected to definitive approval.

In the present work, results are shown in terms of tire/road noise levels, without strictly referring to CPX indexes; however, for the sake of simplicity, they are hereafter referred as L_{CPX} values. The set-up is based on the measurement system described in several papers, [24–26] in which the two mandatory free field microphones (1/2 in., equiped with windscreen) are located close the rear right side pneumatic of a self-powered vehicle, far from the exhaust pipe. The instrumental chain meets the requirement of the Type 1 according to the IEC standards. The tyre used is a Michelin XSE 185/65 R15 88T, according to the reference ones identified by the ISO/CD 11819-2 with a tread pattern similar to the B type. Tyre ran less than 5000 km and before starting each measurement session it was driven some minutes to be brought to the operating temperature. During the measurement session, several runs are carried out. Runs are carried out keeping constant the speed at values in the range between 35 km/h and the maximum allowed by the road. In the post-processing step, data analysis is based on the spatial resolution of about 5.84 m (this basic space is called a "section") and the sound pressure level $L_p(i)$ associated to the i-th section is estimated by fitting experimental data of $L_p(i)(j)$ level by the following well-known relationship:

$$L_p(i) = A(i) + B(i)\log\left(\frac{v(i)(j)}{v_0}\right) \quad (1)$$

where $A(i)$ is the sound pressure level at v_0 reference speed, $B(i)$ is the speed coefficient, $v(i)(j)$ is the actual speed at the i-th section and j-th run. The fit is calculated for each section, in third octave band levels in the frequency range of 315–5000 Hz. It is computed using a minimum chi-squared based iterative algorithm, taking into account the asymmetry of the uncertainties derived from the logarithmic conversion. Then, the overall A-weighted equivalent sound pressure level, at the reference speed, associated to the i-th segment, $L_{CPX}(i)$, is obtained through the A-weighted energy-based sum of the third octave bands estimated levels, as required by the ISO 2011 release. Finally, the $L_{CPX}(i)$ levels versus distance are used in order to characterize the road surface by their mean value averaged all along the installation. The A-type uncertainty is then used to estimate the spatial homogeneity, too.

Tire/noise measurements are influenced by measurement conditions (especially meteo-climatic ones). Their effect would

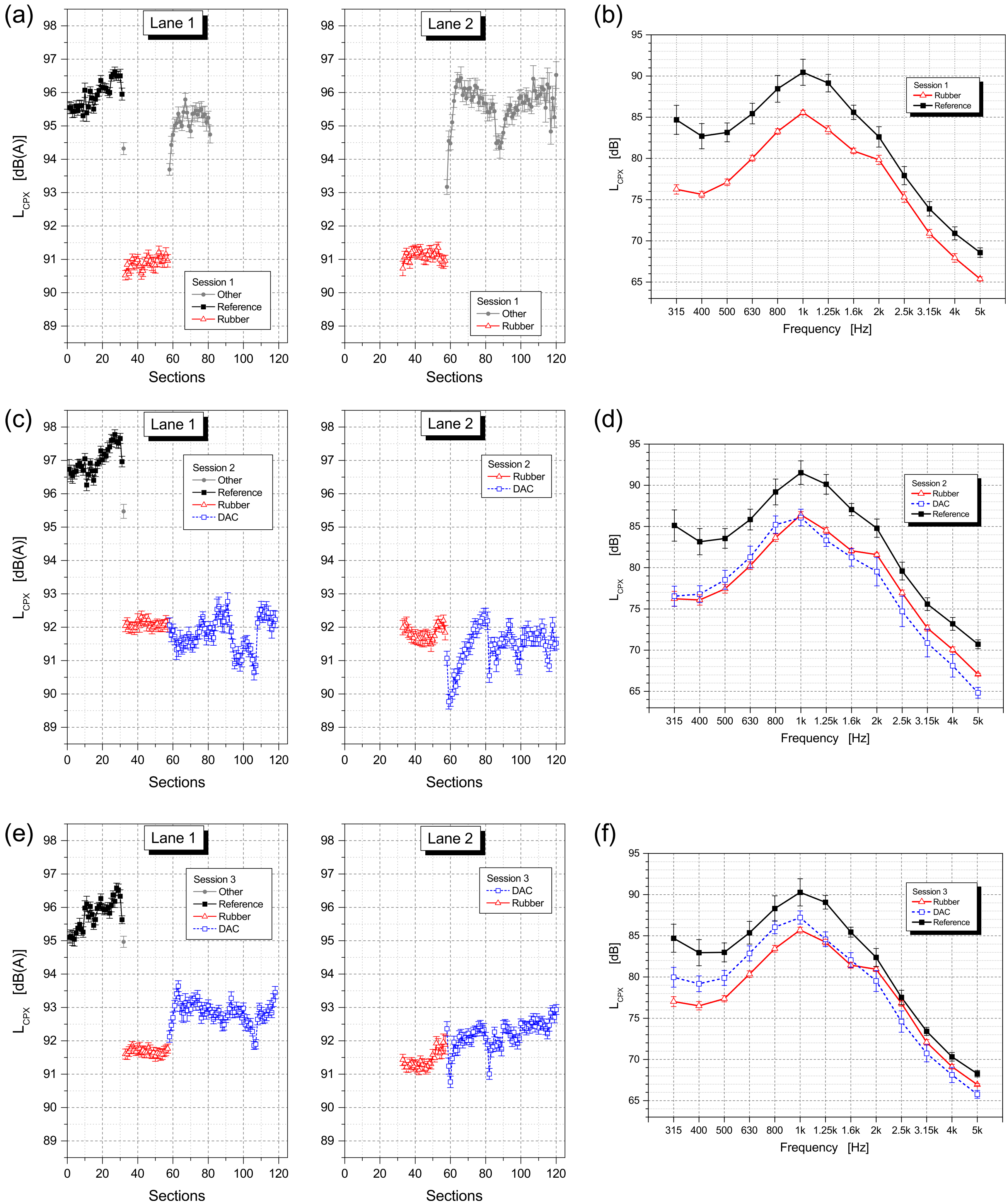

Fig. 1. L_{CPX} time evolution for LEOPOLDO project surface compared to the DAC 0/12 laid next to the special one month later. Measurement sessions 1–3: levels versus distance (figures (a), (c), (e), on the left column) and spectra comparison (figures (b), (d), (f) on the right column). The stretch of rubberized surface is from Section 33–57.

depend on the particular configuration tire/road and in real scenarios it is nearly impossible to find the appropriate correction for each surface surveyed. Moreover, despite in a single measurement session the most of these error sources affect systematically the measurements, they can be assumed as random in case of several measurement sessions carried out in different days and/or with different set-ups or instrumental chains. Thus, comparing absolute values becomes not significant. For this reason, the adapted procedure requires that during the same survey session the measurement has to be extended over a second road surface close to the test one as much as possible. This selected surface then becomes the "*reference*" and the comparison between the two surfaces has

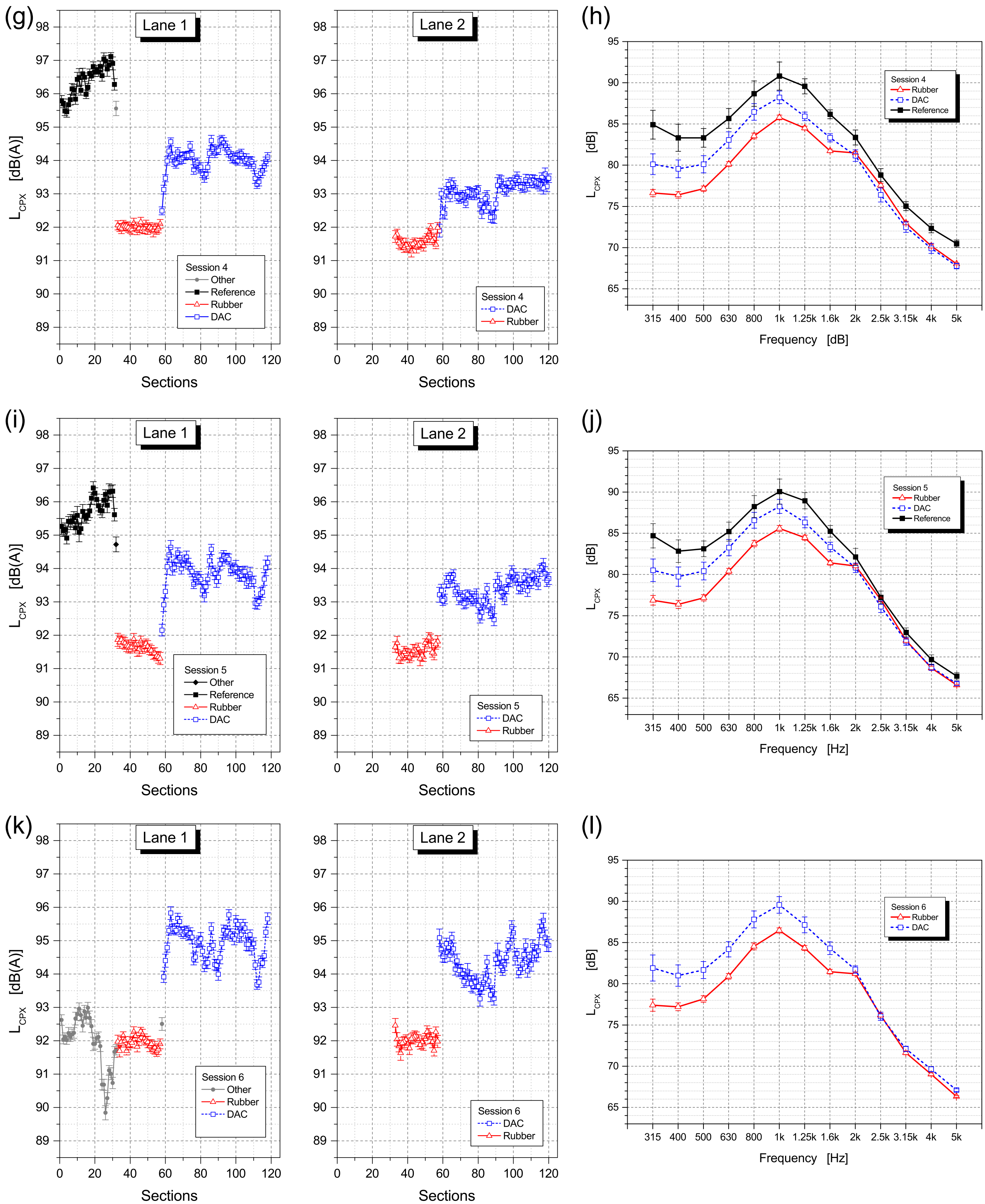

Fig. 2. L_{CPX} time evolution for LEOPOLDO project surface compared to the DAC 0/12 laid next to the special surface one month later. Measurement sessions 4–6: levels versus distance (figures (g), (i) , (k) on the left column) and spectra comparison (figures (h), (j), (l) on the right column). The stretch of rubberized surface is from Section 33–57.

to be carried out to evaluate the acoustical performances of the test one relative to the other one (i.e the noise levels mitigation obtained introducing the new pavement instead of the "*reference*" one). The reference surface could be as equal as possible to the pre-existing, ante-operam one (e.g. long aged and possibly acoustically stable in time), or, alternatively, a road surface coeval to the test one. This choice depends on the purpose of the measurement or the aim of the test surface laying. Save particular cases, the reference surface is always a DAC 0/12, as in this work, or a SMA 0/12 as suggested in [27].

This allows to restrain the unknown error due to measurement meteo-climatical and other conditions of a single measurement to the hypothetical different response to the meteorological conditions by the two surfaces. The choice of this reference surface as equal as possible to the pre-existing one, long aged and possibly acoustically stable in time, or one coeval to the test one depends on the purpose of the measurement or the aim of the test surface laying. This analysis method is called "*the differential criterion*" [23].

2.2. Statistical Pass By method (SPB)

Statistical Pass By methodology is applied to study the influence of the surface on the whole road traffic noise, averaged on a relevant amount of passages.

The procedure applied by ARPAT within the LEOPOLDO project combines the technical international standard with the guidelines provided by HARMONOISE project [27]. HARMONOISE introduces a second measurement position, at 3.0 m height and at 7.5 m far from the central line of the measured lane, to improve the evaluation of the influence of local context, because the ground just outside the road carriage can change with the location and it influences significantly the sound pressure level at the 1.2 m height position. Moreover, the applied procedure is based on measuring the acoustical energy of the various isolated vehicles passing by at different speeds, using the sound exposure level (SEL [28]). During the measurement session, pass-by sound pressure signal and related speed are registered. The instrumental chain meets the requirement of the Type 1 according to the IEC standards. In the post processing analysis, the statistical sample determined by a lot of single passages constitutes the dataset for a logarithmic regression, in accordance with the HARMONOISE project, between the measured speed and the SEL for each microphone.

$$SEL = A + B\log\left(\frac{v}{v_0}\right) \quad (2)$$

where A is the SEL at reference speed and B is a speed-related correction.

Then, the whole procedure is applied to different vehicle categories [29] (defined by weight per axis and number of axes). Eventually the SPB index would be obtained as a specific weighted sum of all categories values. By the way, in this work, results are presented only for the light vehicles category (i.e. the L_1 SPB index) because they are more statistically meaningful (i.e. other vehicle categories were not enough populated).

Table 1
Absolute and differential L_{CPX} spatial average values obtained for the LEOPOLDO project sole rubberized surface, during six measurement sessions along a four years long monitoring. Values are compared to both the reference surface and the coeval DAC one (see text).

Session	Absolute values (dB(A))			Differential values (dB(A))	
	Reference	Rubber	DAC	Rubber	DAC
1	95.8 ± 0.5	90.9 ± 0.1	–	−4.9 ± 0.5	–
2	97.3 ± 0.5	92.3 ± 0.1	91.9 ± 0.4	−5.0 ± 0.5	−5.4 ± 0.4
3	95.8 ± 0.5	91.5 ± 0.1	92.5 ± 0.3	−4.3 ± 0.5	−3.2 ± 0.3
4	96.3 ± 0.5	91.7 ± 0.1	93.4 ± 0.3	−4.6 ± 0.5	−2.8 ± 0.3
5	95.7 ± 0.5	91.6 ± 0.1	93.6 ± 0.3	−4.1 ± 0.5	−2.1 ± 0.3
6	–	92.1 ± 0.1	94.8 ± 0.4	–	–

3. Results

3.1. A case study: the LEOPOLDO project site

The first rubberized surface here analyzed is one of the experimental pavements laid within the LEOPOLDO project [30]. This experimental surface is a gap graded 0/8 with a bitumen mixture modified by the addition of rubber crumb recycled from scrap tires, through the wet process [31]. The reference surface is a part of the pre-existing pavement, a long aged DAC 0/12. Furthermore, after one month a DAC 0/12 surface was laid next to the rubber surface, allowing the evaluation of their different time evolution. The CPX and SPB methods were applied in six measurement sessions, carrying out a four year long monitoring of the acoustical performances of road surfaces.

3.1.1. CPX results

In Figs. 1 and 2 the L_{CPX} time evolution is shown for the six measurement sessions. The emission spectra are shown for each measurement session too. All L_{CPX} values are calculated at the reference speed $v_0 = 50$ km/h.

Absolute L_{CPX} spatial averages are reported in Table 1 (values are corrected for the air temperature according to the standard [12]) for the project rubberized surface, the reference surface and the new DAC coeval to the rubberized surface. L_{CPX} differential values obtained as the difference between rubberized and reference surface and between coeval DAC and reference are also reported in the same Table 1 and plotted in Fig. 3(a).

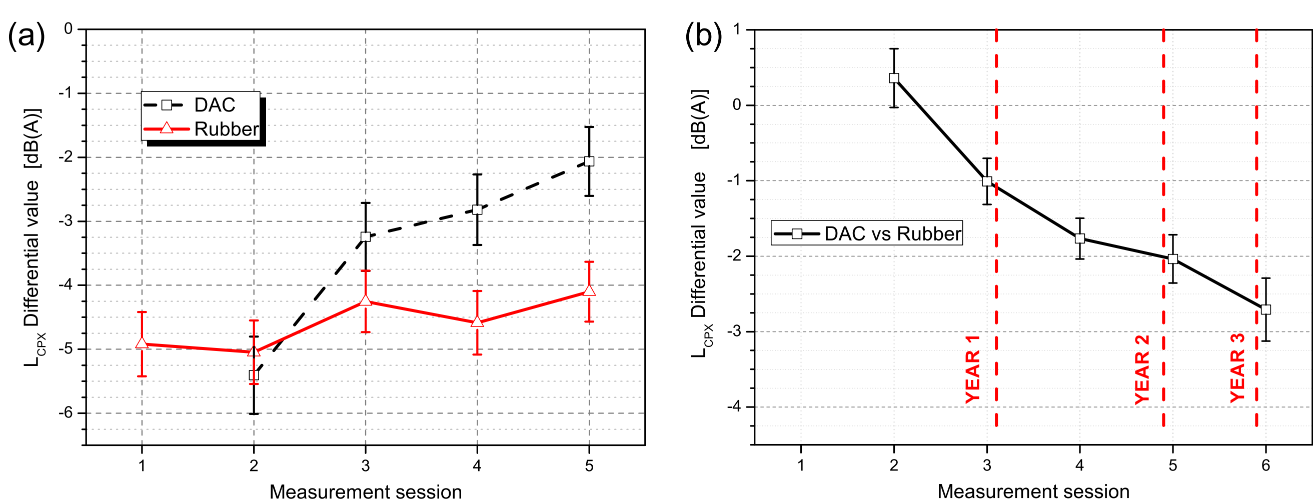

Fig. 3. (a) Time evolution of L_{CPX} differential values computed versus the reference surface; (b) time evolution of L_{CPX} differential values obtained as difference between LEOPOLDO project rubberized surface and DAC coeval one. The age of surfaces is indicated by vertical lines.

Table 2
L_{CPX} differential values between the LEOPOLDO rubberized surface and the next DAC surface (in the first measurement session the DAC stretch was not laid yet).

Session	Differential values [dB(A)]
1	–
2	0.4 ± 0.4
3	−1.0 ± 0.3
4	−1.8 ± 0.3
5	−2.0 ± 0.3
6	−2.7 ± 0.3

The rubberized surface installation shows a good spatial homogeneity and the L_{CPX} differential values between rubberized and reference surfaces are significantly constant in time. On the contrary, the coeval DAC installation does not show a spatial homogeneity and the L_{CPX} value increases significantly in time, reducing the difference with the reference surface. In terms of emission spectrum, no significant shape differences can be highlighted among the three surfaces analyzed. There is just a little secondary peak at 2 kHz for the rubberized surface. L_{CPX} differential values obtained for rubberized surface compared to the DAC one are reported in Table 2 and plotted in Fig. 3(b). The experimental rubberized installation shows a good stability in time, better than the coeval DAC one, and its efficacy is significantly remarkable.

3.1.2. SPB results

In Fig. 4(a) the L_1 SPB values obtained in five measurement sessions spread over three years are shown. In Fig. 4(b) analogous values obtained during the same sessions, but just measuring only the CPX vehicle pass-by, are shown. In this latter case, measurement principles and configuration are the same of the CPB method (Controlled Pass-by [32]), but values were calculated also at the 3.0 m height microphone to compare them with SPB results.

In Table 3 results and sessions details are reported; all values are calculated at the reference speed v_0 = 70 km/h.

Typically, in the SPB measurement carried out along a normal road (i.e. not in a test track), data are distributed as a cloud centered around the “characteristic” or modal road speed (i.e. the speed of the most of vehicles pass-by, close to the speed limit), in this case 70 km/h. Sample size is different for each measurement session, as shown in Table 3, and their speed distribution, shown in Fig. 5, can influence the SEL vs. speed regression slope. These are the two main reasons to evaluate values at the modal speed value, not always equal to the SPB reference speeds (50, 80 or 110 km/h for light vehicles).

The regression coefficients for the SPB fits are always lower than 0.8, whereas for CPB fits they are always higher than 0.95. Although CPB results show more precision, their time distribution does not match neither with the SPB results nor with the CPX results already shown. Not even temperatures, detailed in Table 3, are enough to justify the SPB results and their difference with the CPX ones.

Evidently, the pass-by methods, applied as standard declares, suffers the variability of propagation mechanisms as much as the real physical information about the tire-road noise emission is almost hidden. Analogous conclusions have been found within the SILVIA project [33]. Modified procedures in order to increase pass-by method accuracy are matter of further research.

3.2. Rubber surfaces 1 year old

Beyond the research activity in the LEOPOLDO project, ARPAT executes noise controls in order to verify the respect of noise limits provided by regulations. Within this activity, it has monitored three rubber surfaces with the CPX method, besides the LEOPOLDO project one. A comparison between them, using data obtained one year after the installation, is then possible. One year is distant enough from the first period (lasting few months) after the laying, in which surfaces are still settling down structurally and acoustically [34].

The four surfaces were laid on urban or extra-urban roads and every one was exposed at high traffic density, but within different kind of Italian weather conditions and climatic areas (plain, hill and mountain ground, close to or far from the sea, sunny or shady, with narrow or wide air temperature range, etc.).

In Table 4 surfaces and installation details are reported. All the surfaces depths here analyzed are between 3 and 5 cm. In Table 5 spatially averaged L_{CPX} at 50 km/h are reported, in terms of both absolute and differential values, with related uncertainties (only the statistical one).

Results are obtained as arithmetic mean of both lanes. The fit algorithm used to calculate the level in each section is very robust, so the main part of the uncertainty associated to the spatial average values arises from the spatial variability of the data within and

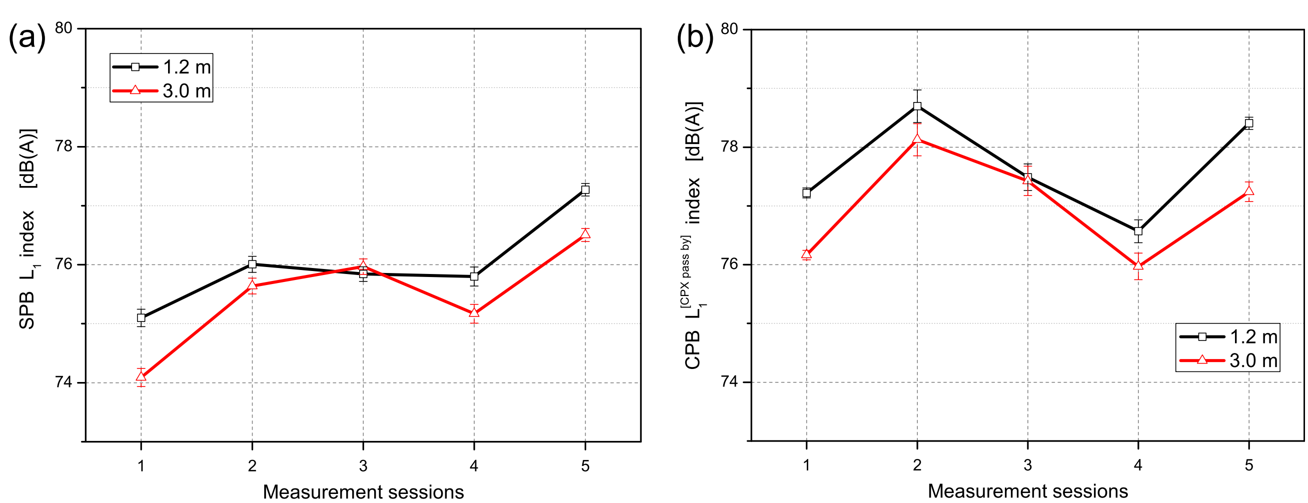

Fig. 4. (a) SPB L_1 index results at 70 km/h of rubberized surface; (b) CPB L_1 index results limited to monitored car pass-bys at 70 km/h obtained during the same measurement sessions.

Table 3
Comparison between L_1 SPB and L_1 CPB values obtained at the LEOPOLDO project rubberized surface site. The subscripts 1.2 or 3.0 means values related to data measured at 1.2 or 3.0 m above the ground. All values are calculated at the reference speed v_0 = 70 km/h. "Ses." it's the abbreviation of "Session"; "Num." means the number of the available pass-bys used for the fit; R^2 is the coefficient of determination for the linear regression.

Ses. ID	T (°C)	SPB					CPB				
		Num.	$L^{SPB}_{1;1.2}$ (dB(A))	$R^2_{1.2}$	$L^{SPB}_{1;3.0}$ (dB(A))	$R^2_{3.0}$	Num.	$L^{CPB}_{1;1.2}$ (dB(A))	$R^2_{1.2}$	$L^{CPB}_{1;3.0}$ (dB(A))	$R^2_{3.0}$
1	10	86	75.1 ± 0.1	0.67	74.1 ± 0.2	0.64	8	77.2 ± 0.1	0.99	76.2 ± 0.1	0.99
2	21	157	76.0 ± 0.1	0.63	75.6 ± 0.1	0.63	7	78.7 ± 0.3	0.98	78.1 ± 0.3	0.98
3	23	102	75.8 ± 0.1	0.78	76.0 ± 0.1	0.76	7	77.5 ± 0.2	0.99	77.4 ± 0.2	0.99
4	21	66	75.8 ± 0.1	0.67	75.2 ± 0.2	0.70	6	76.6 ± 0.2	0.96	76.0 ± 0.2	0.95
5	15	146	77.3 ± 0.1	0.72	76.5 ± 0.1	0.70	5	78.4 ± 0.1	0.99	77.2 ± 0.2	0.99

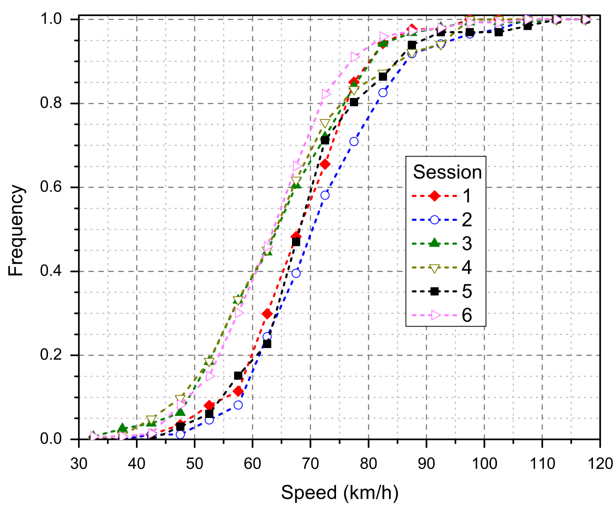

Fig. 5. Experimental speed distributions for data collected in the five SPB measurement sessions.

between lanes. Results reported in Table 5 are corrected for air temperature.

In terms of absolute values, surface 1 and 4 have the same value of nearly 91.5 dB(A), whereas surface 2 and 3 report different levels, respectively 2.5 dB(A) lower and about 1.0 dB(A) higher. Anyway, in terms of differential values, surface 1 and 2 have a lower sound emission estimated in respectively about 4.7 and 6.2 dB(A). These results are clearly better than those obtained for the other surfaces, showing differential values lower than 3 dB(A). It needs to be emphasized that a 3 dB(A) value is often the minimum gain expected from a surface used as mitigation action [4]. Same conclusions can be drawn from the results obtained at 80 km/h.

The analysis of differential values is determined by the choice of the reference surfaces during the measurement planning, in accordance with the EU projects HARMONOISE/IMAGINE position paper (see [29]). They are all close to the test track. They are all DAC 0/12, usual in Italy (in Tuscany at least), with installation older than 4–5 year, without apparent damages and discontinuities as crack or patches, and they are surveyed at the same time as the tested rubberized surfaces in order to minimize the measurement condition influence. Nevertheless, the absolute L_{CPX} values of reference surfaces are not all comparable, because of a potential different wear (meteorological conditions, traffic density...) and because of the influence of the measurement conditions.

Finally, it needs to be underlined that in case of surface 3, the real benefit of using this rubberized surface as mitigation action is a lower emission level of 1.2 dB(A) than the reference DAC 0/12. In case of surface 2 the real benefit is more than 6.0 dB(A) and it is surely more effective.

The frequency analysis is the last way to compare the four surfaces here used. In Fig. 6 the *normalized* third octave bands spectra are shown.

This type of spectrum, also seen in the ISO 1793 series [35] for normalizing the acoustic response of barriers, has the total energy sum always equal to 0 dB. It allows to compare different emission energy spectra (here in 1/3 octave bands) in order to identify the specific frequency behaviors.

All surfaces show a spectral peak at 1000 Hz, with the same relative intensity. The only shape details noteworthy are the secondary spectral peak at 2000 Hz shown by surfaces 1 and 2, and the low frequency levels (500–630 Hz) of surface 2 being higher

Table 4
One year old rubberized surfaces: some installation details.

ID	Site	Surface	Area	Length (m)	Temperature (°C)
1	Le Panche (LEOPOLDO)	WET (0/8)	Mountain	150	23
2	Livorno	WET (0/12.5)	Plain	800	22
3	Signa	DRY (0/6)	Hill	950	17
4	Borgo a Buggiano	WET (0/12)	Plain	450	35

Table 5
L_{CPX} spatially averaged values at 50 km/h for the four rubberized surfaces here analyzed, their respective reference surfaces and corresponding differential values calculated at 50 km/h, too.

Surface	Rubber	Reference	Differential
1	91.7 ± 0.1 dB(A)	96.4 ± 0.5 dB(A)	−4.7 ± 0.5 dB(A)
2	88.8 ± 0.6 dB(A)	95.0 ± 1.7 dB(A)	−6.2 ± 1.8 dB(A)
3	92.8 ± 0.4 dB(A)	94.0 ± 0.3 dB(A)	−1.2 ± 0.6 dB(A)
4	91.6 ± 0.8 dB(A)	93.5 ± 0.6 dB(A)	−1.8 ± 1.0 dB(A)

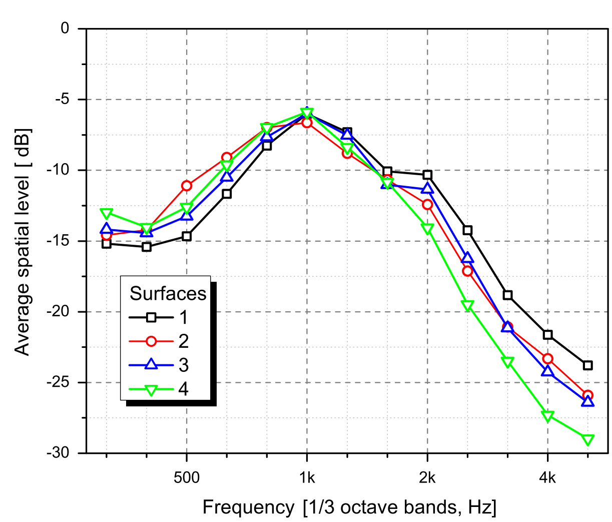

Fig. 6. Spatial mean spectra of the measured rubberized surfaces.

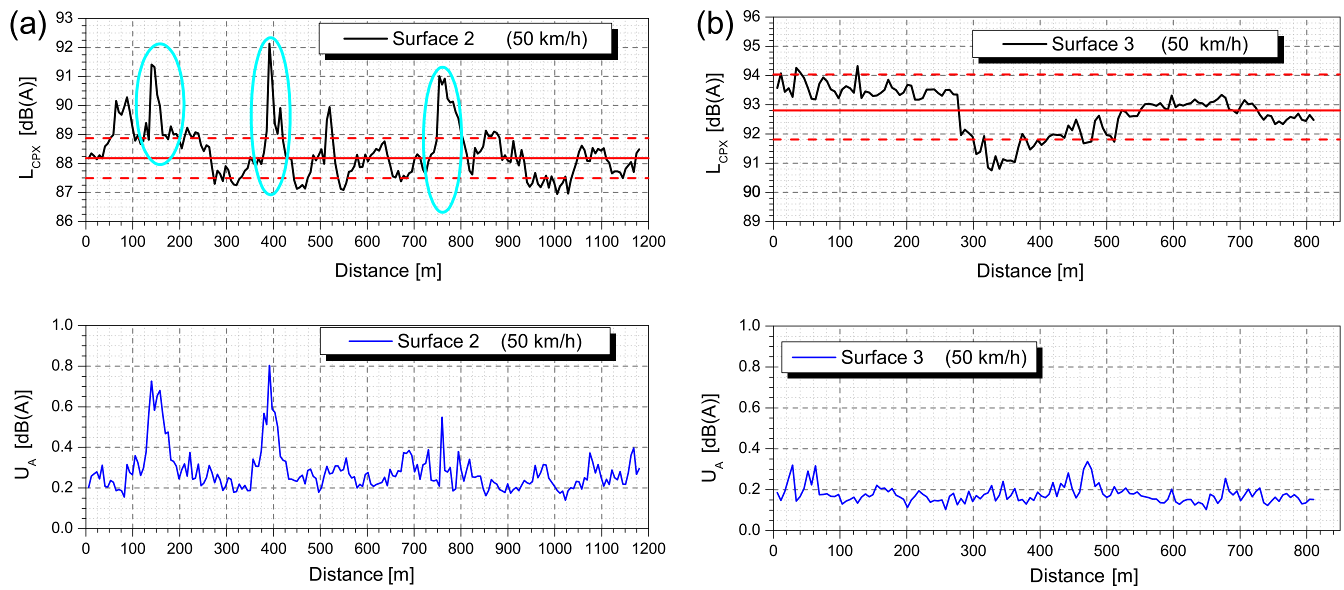

Fig. 7. L_{CPX} values versus distance (upper figures) and their type A uncertainties (lower figures) for surfaces 2 (a) and 3 (b). In upper figures red solid lines indicate the spatial mean and red dashed ones are plotted to represent the 1 standard deviation distance from the mean. Only type A uncertainty is here considered with coverage factor $k \approx 1$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than other surfaces. The secondary spectral peak for surface 1 and 2 have no remarkable effect on the L_{CPX} values because levels at 2000 Hz are 4 dB(A) lower than the 1000 Hz ones and slightly influences the overall level. On the contrary, a shifting energy towards low frequencies produces a significantly lower overall level, through to the A-weighing. Surely, this is one of the reasons for the good performance of surface 2. Anyway the frequency analysis is not able to justify the differences among the surfaces.

3.2.1. Discussions

The wide spread of differential values is an important issue, because when road surfaces are laid as mitigation actions, they should guarantee the results, to avoid recurring of the noise limit excess and incurring further costs. Moreover, the spatial homogeneity plays a lead role to ensure the mitigation action efficacy along the whole installation. It cannot be left out in the acoustical performance assessment. Thus, spatial variability of data is a further issue to be considered.

Different results found for the four surfaces cannot be completely associated to the different rubberized asphalt techniques, because no clear pattern can be found among these and L_{CPX} levels (see Tables 4 and 5). This variability may be explained by the quality of the pavement installations, which depends on the ability of the installer, on the materials used and on the adherence to the technical construction notes for the special pavement. In some cases, this statement is clearly demonstrated by the spatial homogeneity analysis, by means of data variability of the L_{CPX} values versus distance. For short stretches, as the 150 m long LEOPOLDO project surface, the spatial variability is limited, while for long stretches it can reach values even comparable to the expected attenuation. This spatial variability might eventually compromise the efficacy of the mitigation action.

Data spatial variability within an installation can occur in two different forms, as is highlighted by Fig. 7(a) and (b), where L_{CPX} values versus distance are plotted in case of both surface 2 and surface 3, with their spatially averaged value over the entire stretch and the associated one standard deviation region (the area between the two dashed lines).

Raised crosswalks were present above the pavement of surface 2. Their position are highlighted using ellipses in Fig. 7(a). Noise levels raises up to several dB(A) (from 3 to 5 as in figure) while passing on these elements. The raised crosswalks have been built above the pavement and after its installation, so works could have modified the adjacent parts of the rubberized surface. Moreover, the test car needed to slow down when approaching the crosswalks and then accelerate after, limiting the goodness of the measurement session. This constraint to the measurement speed implies not well known influences of the acceleration on data and, above all, a limitation of speed range in the calculation data.

The clear effect of this speed flattening in the calculus of the fit can be easily found on the magnitude of the corresponding uncertainty associated to the results, shown in the bottom part of the figures. After removing the circled parts, the remaining levels vary about 2–2.5 dB(A): this is still a not negligible variance, which leads to the 0.6 dB(A) of uncertainty associated to the spatial average value (shown in dashed lines).

In case of surface 3, Fig. 7(b), levels show a big discontinuity, not recognizable in the magnitude of uncertainty versus distance. This makes the surface looks like as it was separated in two stretches, among which the second one shows a clear spatial trend. As for surface 2, the variance is high, leading to the 0.7 dB(A) of uncertainty associated to the spatial average value. However, it must be noticed that the levels vary within 1.0 dB(A) around a nearly constant value in the first part and around the trend curve in the second one.

Finally, the quality of the installation could influence the acoustical level emission, in term of both relative values (homogeneity) and absolute values, as shown in the previous analysis of the spatial data variability. Particularly, for surface 3, data show that an installation with an emission level lower than 92.0 dB(A) could have been possible, which would have led to a more significant differential value.

4. Conclusion

To present day, the use of special low noise emission surfaces can be the only solution to mitigate noise for roads with high and continuous traffic flows, especially in urban or extra-urban contexts. Rubberized surface is one of the most used low emission solution in the world and it is going to become established also in

Italy. Some rubberized surfaces have been used as experimental mitigation actions in Tuscany.

Four different installations were surveyed with the CPX method to compare their acoustic behavior one year after the laying. Moreover, a rubberized surface has been laid within the LEOPOLDO project (an experimental project co-funded by Tuscany Region and Italian Ministry of Transportation) and inside this project, it was possible to monitor its acoustical time-stability with both CPX and SPB methods for several years.

All the surfaces here analyzed have no special absorption behavior (no open surfaces were present). Analysis has been performed both wideband or as a function of frequency.

In terms of L_{CPX} values, the LEOPOLDO project surface shows a good spatial homogeneity and a significant noise emission reduction if compared to both its respective *ante operam* surface and a DAC surface laid next to rubberized one at the same time. Moreover, this acoustical behavior is stable in time.

On the other side, SPB results obtained in five different measurement sessions spread over three years are not capable to accurately describe the contribution of the tire/road noise emission of this surface propagated at roadsides.

Not even CPB results, obtained considering only the CPX vehicle pass-bys, match in any way with the results expected from the CPX data. Moreover, modified procedures will be necessary in order to increase pass-by method accuracy and they are going to be matter of further research.

Besides the LEOPOLDO project experience, other four different rubberized surface installations were analyzed through the CPX method. The comparison among them showed variable results, with differential values between about 1 and 6 dB(A). It is argued that the main reason to this variability might be the quality of pavement installation. Also the spatial homogeneity plays a lead role, as shown in some analysis of the L_{CPX} levels along the installation.

As clearly demonstrated with two different cases analyzed, the rubberized surface solution can represent a very efficient and well adaptable mitigation action, especially in an urban context where other solutions cannot be applied (i.e. barriers, flow control or open-graded surfaces). In order to avoid action uselessness, it must be considered that the installation of this kind of surface needs care and proficiency complying with the technical specifications.

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