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Modelling the acoustic performance of newly laid low-noise pavements

Luca Teti [a], Gonzalo de León [b], Lara Ginevra Del Pizzo [b], Antonino Moro [c], Francesco Bianco [a], Luca Fredianelli [b], Gaetano Licitra [d,*]

[a] IPOOL S.r.l., Pisa, Italy
[b] University of Pisa, Physics Department, Pisa, Italy
[c] CNR-IPCF, Via Moruzzi 1, 56124 Pisa, Italy
[d] ARPAT – Environmental Protection Agency of Tuscany Region, Via Vittorio Veneto 27, 56127, Pisa, Italy

HIGHLIGHTS

- The use of low-noise surfaces is the best solution to mitigate tyre/road noise.
- Green Public Procurement (GPP) requires CPX measurements on new low-noise pavements.
- Modelling CPX levels in function of the mix properties is necessary to reduce costs.
- Two models were elaborated, using two frequency separations for tyre/road noise.
- The variables used are related to volumetric and composition properties of the mix.

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ABSTRACT

Road traffic in urban contexts produces noise mainly by the interaction of tyres with pavement surface and, therefore, the use of low-noise surfaces represents the best solution since they aim to mitigate the source. Moreover, in urban contexts it is often the only viable solution, together with a careful traffic planning. The main challenge in their adoption as noise mitigation actions is to be able to forecast the acoustical performances that the new road surface will be able to offer. In the UE, the new Green Public Procurement requires experimental verification of noise performance compliance: the designer must declare the acoustical performance of the proposed low-noise pavement and, a few months after the laying, the actual performance of the road surface must be tested using the Close Proximity Method (CPX). Due to the importance of being able to forecast CPX levels, the present work reports a novel way to model CPX broadband levels of newly laid low-noise road surfaces using only data available to the designer before the laying or easily obtained through coring tests, such as grading curve, fractal dimension, asphalt binder content, air voids, voids in mineral aggregates. Two models were elaborated, using two different frequency separations for tyre/road noise. The first model separates low and high frequency contributions, while the second one also considers noise around 1 kHz separately, using a three-band model. Both models are capable of forecasting the acoustic performance of newly laid low-noise road surfaces, using different road mixture parameters at different frequency ranges. The three band model shows a lower RMSE.

1. Introduction

Transport infrastructure are well-known sources of noise [1], affecting the wellness of modern society, with roads as the most diffused and impacting one in urbanized areas. Indeed, even after 15 years from the 2002 European Environmental Noise Directive (END) emission, a revision [2] reported that "about 100 million people in the 33 EU member states are exposed to an average sound level due to traffic over a 24-hour period (L_{DEN}) exceeding 55 dB(A), and 32 million are exposed to noise levels higher than 65 dB(A) of L_{DEN}". Such levels could lead to a series of issues, i.e. sleep disorders with awakenings [3–5], partial deafness [6,7] cardiovascular diseases [8,9], annoyance [1,10–12]. In order to mitigate such problems, competent authorities periodically fund proper action plans, as demanded by the END [13], while in the last years the goal of the scientific community is the deepening of the knowledge of noise generation mechanisms and optimization of mitigation actions [14].

* Corresponding author.
E-mail address: g.licitra@arpat.toscana.it (G. Licitra).

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Road traffic noise is due to different sources: the engine, whose contribution is significant only at low speeds, aerodynamic turbulence due to the vehicle motion through the air, and tyre-road interaction, which represents the main contribution for speeds that cover a wide range, from 30 to 120 km/h [15].

Tyre/road noise combines aerodynamic and a structural mechanisms of noise generation. Aerodynamic noise is related to air pumping [16], generating noise at frequencies higher than 1 kHz, and to pipe and Helmholtz resonances, due to the coupling of a vibrating mass of air within the tread, which acts as a cavity [15]. Structural or vibrodynamic noise is produced by the interaction of the tyre with pavement irregularities and covers frequencies lower than 1 kHz. It is also caused by non-linear effects such as the "stick-and-slip and stick-and-snap mechanisms" [17]. While the former is caused by the motion of the tyre tread with respect to the surface, the latter is present when the grip on the tyre is too strong, as it can happen on newly laid road surfaces.

In this context, studies aiming to optimise road textures or mixture designs have become increasingly popular in order to mitigate noise since the last decade [18–20] and regulations such as the Regulation E.U. No 1222/2009 [21] have been published in order to suggest tyre characteristics that are useful to decrease tyre/road noise. In the meanwhile, the European studies SilVia [22], HARMONOISE [23], QCITY [24] and SILENCE [25] focused on actions based on low emission road surfaces, including the methods to evaluate their effectiveness. Results showed that road pavements which incorporate rubber deriving from end-of-life tyres represent an effective solution. Besides reducing noise, the use of rubber has also the great environmental benefit of recycling rubber, meeting modern green and circular economy requests [26,27]. In particular, Porous Elastic Road Surfaces (PERS) [28–30] use rubber as main component of the mix, while rubberized surfaces mix rubber with common asphalt components [31].

The acoustical performances of these pavements are in constant monitoring since their birth: PERS reduce noise in roadside levels of about 10 dB(A) if compared to traditional surfaces [32–34] and provide a very elastic surface, thus greatly reducing vibrodynamic noise. However, these surfaces are not yet widespread on the Italian territory and several issues were found out in a Japanese study [35]. On the contrary, rubberized surfaces have gained popularity in Italy and provide also a greater noise reduction, compared to traditional road surfaces [36,37]. The Leopoldo project and several studies were carried out in order to monitor the acoustical performances of rubberized pavements and assess their effectiveness as a mitigation action [38–40].

For new low-emission pavements, the European legislation GPP [41] has recently prescribed acoustic tests by means of the CPX method [42] during the first 3 months from laying date. Therefore, forecasting the acoustic performance of a pavement in terms of the CPX level from the job mix formula now covers an extremely important role, since it could lead to considerable time and money savings. The importance of deriving the acoustical performance of pavements from their mix design is confirmed in previous works [43,44].

The correlation between noise and composition and volumetric parameters was studied in 2013 by Losa et al. [45]. In this work, tyre/road noise produced by a reference tyre was obtained using a linear function of asphalt mix characteristics. The study was based on measurements of CPX levels and composition and volumetric parameters of pavements of different ages, but recently some works [46,47] show that acoustic ageing of pavements is also dependent on both traffic loads and climatic conditions.

The objective of the present work is to establish a model able to forecast the CPX level (L_{CPX}) from the job mix formula for newly laid pavement surfaces using data from newly-laid road surfaces, starting from the same parameters proposed by Losa [44] and using a set of CPX measurements performed by a National Research Council of Italy spin-off company, IPOOL srl,. The model could represent a useful tool for complying the GPP requests, which require for newly laid surfaces a specific acoustical test based on the CPX protocol.

2. Methods

Due to its importance among EU regulations [41], tyre/road noise was evaluated using the CPX method, as defined in ISO 11819-2 [43]. As already stated, the objective of this work is to create a model based on road surface volumetric and mixture parameters for estimating the CPX level obtained on newly laid road surfaces.

The parameters used for modelling CPX noise levels are:

1. Asphalt binder content *B*% referred to aggregate weight (UNI EN 12697-1);
2. Sieve diameters (or aggregate sizes) D_x through which a percentage *x* of the aggregate mass is able to pass. For each pavement, aggregate grading curve was determined (UNI EN 12697-2). Subsequently, the diameters D_x were obtained via linear interpolation with steps of 5%;
3. Fractal dimension (D_f);
4. Air voids content V_A (UNI EN 12697-8);
5. Percentage of voids in mineral aggregates on the total volume *VMA* (UNI EN 12697-8).

While these parameters represent only a small subset of the variables that describe road surfaces, these properties were chosen since they are determinant in the design phase when choosing the optimal mix and they can be easily measured by on-site coring tests. It has been noted [46] that each one of the parameters used represents a different property of the road surface: in particular, while aggregate grading and fractal dimension are representative of texture properties, air voids percentage and voids in mineral aggregates are related to absorption properties.

The V_A are "small airspaces that occur between the aggregate particles in the final compacted mix", while *VMA* are defined as "the volume of inter-granular void spaces between the aggregate particles of a compacted pavement mixture including the air voids and the effective asphalt content, expressed as a percentage of the total volume of the specimen" [48]. It is customary to express both V_A, *VMA* as a fraction of total volume, while *B*% and the aggregate grading are expressed as a fraction of weight. Fig. 1 further explains the relation between the different parameters chosen in this study.

Aggregate grading, used to derive both fractal dimension D_f and the diameters D_x, is performed by sieving the sample through a set of sieves and measuring the passing rate of aggregates $P(r)$ for each sieve. Following the calculations reported in [41] the mass fractal dimension D_f is related to the passing rate as follows:

$$P(r) = \frac{M(r)}{M} = \frac{r^{3-D_f} - r_{min}^{3-D_f}}{r_{max}^{3-D_f} - r_{min}^{3-D_f}} \tag{1}$$

where M is the total mass of the aggregates, $M(r)$ represents the mass of particles with radius $\leq r$, and r_{max} and r_{min} are the maximum and minimum radius of particles. For fine aggregates, r_{min} can be neglected, thus Eq. (1) becomes:

$$P(r) = \frac{M(r)}{M} = \left(\frac{r}{r_{max}}\right)^{3-D_f} \tag{2}$$

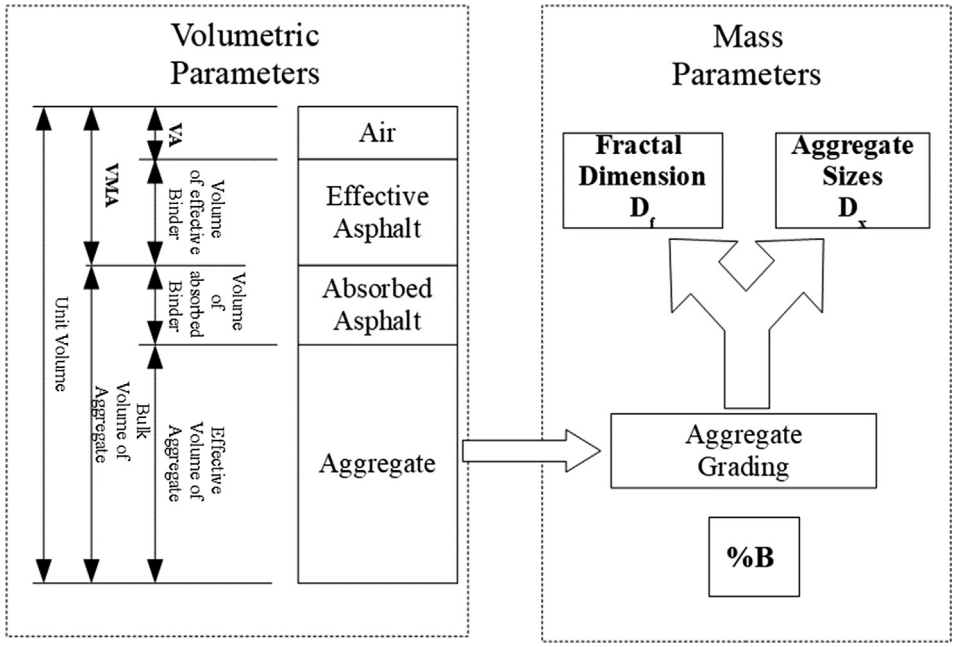

Fig. 1. Volumetric and mass parameters for HMA. Parameters used in this work are represented in bold.

Eq. (2) can be recast in the form:

$$D_f = 3 - \frac{\ln P(r)}{\ln \frac{r}{r_{max}}} \tag{3}$$

showing that the fractal dimension is an adimensional quantity that varies between 2 and 3. The fractal dimension is "an index that measures the degree of complexity how fast our measurements increase or decrease as our scale becomes larger or smaller" [49]. In this case the concept of fractal dimension is a generalization of a classical concept of integer dimension, i.e. how many times a self-similar object is divisible for a scale factor as defined in [41] and reflects how the configuration of the solid structure is represented by the aggregates.

CPX measurements have been carried out by means of a modified protocol, described in previous works [50], which is able to provide results with high accuracy and to estimate the related uncertainty. In order to obtain adequate statistics in terms of data variability and sample size, the measurements used in this work were all performed before the last ISO 11819-2 was released in 2017 and therefore the reference tyre was a Michelin Energy XSE 185/65 R15 88T.

The CPX method aims at the evaluation of the acoustical properties of road surfaces, measuring tyre/road noise using two microphones located close to the reference tyres, as shown in Fig. 2.

During the measurement sessions, at least 8 runs for each pavement surface were performed at different speeds. The energetic average of the sound pressure level measured by both microphones was calculated on each road surface, using a spatial resolution of 6.18 m. During post-processing, the energetic average of the sound pressure level recorded by both microphones was fitted with speed within each section with the well-known logarithmic relationship [15,42], using a minimum χ^2 iterative algorithm. Using a reference speed of 50 km/h and performing hardness and temperature corrections as described by ISO 11819:2 [42], mean CPX levels in one-third octave bands were calculated for each road surface.

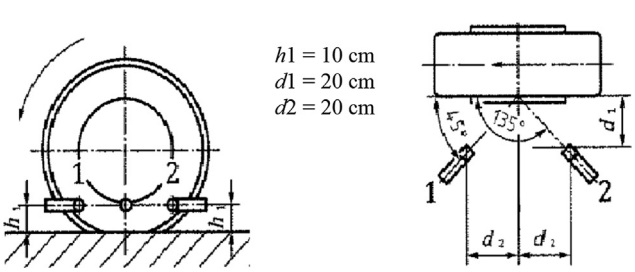

Fig. 2. Microphone positioning for CPX measurements. Figure modified from ISO 11819–2:2017 [42].

Hardness and temperature corrections proposed by the current release are strictly valid only for broadband levels, however, due to the absence of studies concerning this issue in current literature, CPX levels in one-third octave bands were also corrected in temperature and hardness using the same relation.

Results of CPX measurements were divided in separate frequency ranges, by defining wide-bands derived from the one-third octave spectra, and the resulting wide-bands were correlated to road mixture properties through a stepwise-like regression using a forward selection approach [51], which consists in adding iteratively explanatory variables to the models using correlation analysis. The purpose of the stepwise-like iterative algorithm is to avoid the presence of collinear explanatory variables within the model. Multivariate linear regressions were then performed between the statistically significant variables and wide-bands tyre/road noise levels. In principle, the relation between tyre/road noise and road mixture parameters could be much more complicated; however, a linear model was chosen to easily pinpoint the effect of the different variables on tyre/road noise.

3. Experimental sites

The analysis was carried out on a set of 12 low noise pavements laid on inter-urban roads in Italy in the area of Bolzano, Bologna and Rome. The time evolution of the acoustic properties of the road surfaces is also available and has been monitored with CPX over almost a whole decade but, since this work focuses on modelling the CPX levels shortly after laying, this data was only used to check the fitness of the road surfaces, since eventual defects could lead to

a faster degradation of the acoustic performance of these surfaces. Table 1 details the sites analysed, showing for each surface its ID, pavement type, crumb rubber recycling process, mix and volumetric characteristics and the age of the pavement. Figs. 3–5 report gradation curves for the analysed mixes, summarised in Table 2.

As it can be inferred from Table 1, the sample studied includes dense asphalt concrete and gap graded surfaces and rubberized surfaces, divided in wet and dry according to their recycling process of rubber in pavement. These pavements were chosen since they are the most common low-noise road surfaces available in Italian territory.

In the pavements produced according to the wet process, crumb rubber is blended with liquid asphalt cement (AC) before mixing AC with the aggregate. According to ASTM [52], asphalt rubber is "a blend of asphalt binder, reclaimed tyre rubber and additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt binder sufficiently to cause the swelling to the rubber particles". Therefore, in the wet process, the crumb rubber absorbs a portion of the bitumen oily phase, causing swelling of the rubber particles and thus leading to an increase of viscosity [53]. In the dry process, crumb rubber is added to the hot aggregate in 1–3% of the weight of the total mixture before adding the asphalt cement. This process was developed in Sweden during the '60 s, while it spread in the USA in the late 80's and reached many European countries only in year 2000 [26].

For the development of the CPX model from road parameters, dense or gap graded surfaces (ID 1 to 10) were used, whereas the two open graded surfaces (ID 11 and 12) were only tested but not used for modelling, since their small number could not provide information regarding their acoustic behaviour.

4. Development of the multivariate model

The original model proposed by Losa et al. [44], used as a starting point in this work, describes broadband CPX levels as a linear combination of the ratio of the diameter of the 95th percentile passing sieve (D_{95}) and the fractal dimension D_f, and the ratio of V_A and VMA:

$$L_{CPX} = C_1 + C_2 \frac{D_{95}}{D_f} + C_3 \frac{V_A}{VMA} \quad (4)$$

The study was performed using CPX levels at two different speeds, thus including the logarithmic dependence on speed.

As stated in the study, the ratio between D_{95} and D_f "is an optimal indicator of the diameter encountered by the tyre", while the ratio between V_A and VMA takes into account the acoustic absorption properties of road surfaces [44].

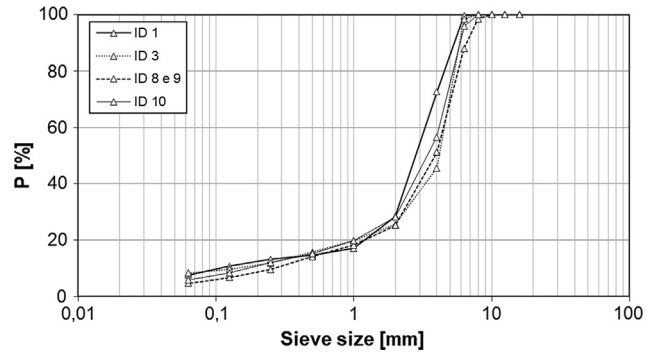

Fig. 3. Gradation Curve for Gap Graded 0/8 and 0/6.

Fig. 4. Gradation Curve for AR 0/16.

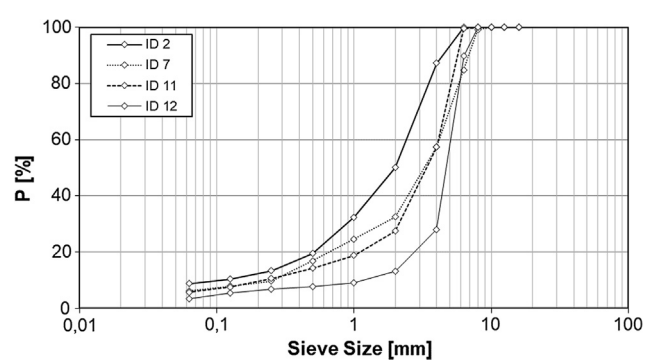

Fig. 5. Gradation Curve for the remaining types of pavements.

Table 1
Investigated pavements.

Site	ID	Pavement Type	RecyclingProcess	Thickness(cm)	B%(%)	V_A(%)	VMA(%)	D_F	Age at survey (Days)
I	1	SMA Gap Graded 0/8 with optimized texture [38]		3	6.8	11.8	25.2	2.453	164
II	2	Dense Graded 0/6 with expanded clay		4	8.5	5.1	19.0	2.612	35
III	3	AR Gap Graded 0/8	Wet	3	8.7	7.3	25.6	2.518	54
IV	4	AR Gap Graded 0/16	Wet	5	8.4	8.0	26.0	2.313	57
IV	5	AR Gap Graded 0/16	Wet	5	8.5	8.1	26.4	2.309	57
V	6	AR Gap Graded 0/16	Wet	4	8.1	8.1	25.0	2.400	57
IV	7	AR Gap Graded 0/9	Wet	5	8.2	8.2	26.0	2.443	57
VI	8	SMA Gap Graded 0/8 with 0.75 RTR	Dry	3	7.5	8.3	22.8	2.375	63
VI	9	SMA Gap Graded 0/8 with 1.20 RTR	Dry	3	8.5	5.4	21.9	2.381	63
VII	10	SMA Gap Graded 0/6 with RTR	Dry	3	8.1	7.9	23.9	2.439	105
VIII	11	Micro-porous Open Graded 0/6		4	4.4	21.4	30	2.414	44
IX	12	Micro-porous Open Graded 0/10		3	4.2	28.5	35.7	2.522	44

Legend: SMA = Stone Mastic Asphalt; RTR = Recycled Tyre Rubber; AR = Rubberized pavement by wet process

Table 2
Aggregate grading of the mixtures.

Sieve Size [mm]	ID1	ID2	ID3	ID4	ID5	ID6	ID7	ID8	ID9	ID10	ID 11	ID 12
16	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	100.0	100.0	100.0	99.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
10	100.0	100.0	100.0	89.5	91.1	89.4	100.0	100.0	100.0	100.0	100.0	100.0
8	100.0	100.0	100.0	76.7	76.9	77.7	99.2	98.1	98.5	100.0	100.0	100.0
6.3	99.70	100.0	98.80	63.7	64.3	64.1	84.8	87.4	88.1	96.0	99.30	89.90
4	72.80	88.00	46.30	36.5	38.6	38.3	57.4	50.5	51.2	56.5	57.30	28.70
2	28.70	50.30	25.40	20.3	21.6	23.1	32.5	24.6	25.2	28.2	27.80	14.00
1	17.40	32.40	20.50	13.2	13.8	17.6	24.6	17.8	18.2	19.8	18.40	9.30
0.5	14.60	18.90	16.70	9.1	9.1	12.0	16.8	13.9	14.2	15.3	13.80	8.20
0.25	13.60	13.50	11.10	6.4	6.3	9.5	9.6	9.5	9.6	12.0	9.90	5.70
0.125	11.10	11.20	10.50	4.4	4.3	7.0	7.9	6.5	6.7	8.5	7.20	6.30
0.063	7.80	8.50	8.90	3.0	2.9	4.5	6.1	4.5	4.7	5.8	5.90	3.60

It is known, however, that noise generation depends not only on large discontinuities represented by the D_{95}, but on shorter lengths too: in particular, high frequency noise, due to air compression within the voids, is related to smaller aggregates. It seems reasonable, therefore, that a more accurate description of tyre/road noise could be achieved by introducing different frequency ranges differently influenced by road surface properties. This provides a theoretical basis for the development of a multi-band model that relates CPX noise levels to the job mix formula of road surfaces using a frequency analysis. In particular, two different models have been developed in this work, which separate differently the frequency regions. The first model uses two different frequency ranges for tyre/road noise, while the second one is a three-band model focusing on the frequency region around 1 kHz, which showed poor correlation with road surface properties in other studies [54,55].

The two models were developed following the same process, based on correlation analysis. At first, the wide-band levels $L_{CPX}(j)$ were defined starting from one-third octave levels and considering A-weighing, according to the equation

$$L_{CPX}(j) = 10\log_{10}\left(\sum_{i=f_1}^{f_2} 10^{0.1\times(L_{CPX}(i)+A_i)}\right) \quad (5)$$

where:

$L_{CPX}(j)$ is the 1/3 octave band level centered in f_i;

f_1 and f_2 are the lowest and highest central frequencies for each wide-band;

A_i is the A-weighted correction according to the International standard IEC 61672:200.

Table 3 shows the selected range for each model:

- for the two band model, the low frequency band sums energy contributions from 315 Hz to 1250 Hz and the high frequency band sums energy contributions from 1600 Hz to 5000 Hz;
- for the three band model the low frequency band sums energy contributions from 315 Hz to 800 Hz, the mid frequency band sums contributions from 1000 Hz to 1600 Hz and the high frequency band sums energy contributions from 2000 Hz to 5000 Hz.

Finally, the broadband L_{CPX} was reconstructed using the wide-band levels, as follows:

$$L_{CPX} = 10\log_{10}\left(\sum_{j=1}^{2\vee 3} 10^{0.1\times L_{CPX}(j)}\right) \quad (6)$$

where the upper index of the summation is equal to 2 for the two-band model and 3 for the three-band one.

The model development process took place using a stepwise-like regression in which the choice of predictive variables was performed by an iterative approach based on the analysis of the correlation between measured CPX wide-band levels and parameters of the surveyed road surface. A concise flowchart of the procedure adopted for developing the model is shown in Fig. 6.

More in detail, the aim of the stepwise-like procedure adopted for developing the model was to highlight the correlation between measured CPX wide-band levels and parameters of the surveyed road surface avoiding the choice of collinear explanatory variables. Naming $L_{CPX}(j)_0$ the CPX level measured for the jth wide band, in the first iteration of the procedure the correlation coefficient was calculated between the jth level and all the input parameters. The most correlated variable was selected and a simple linear regression was performed and the p-value was used for evaluating its significance. If the variable resulted significant, a corrected level named $L_{CPX}(j)_1$ was calculated as follows:

$$L_{CPX}(j)_1 = L_{CPX}(j)_0 - \alpha_1 VAR_1 \quad (7)$$

where VAR_1 is the selected variable and α_1 is the slope obtained from the linear regression. The corrected level defined by Eq. (7) therefore allows to subtract the influence of VAR_1 from the $L_{CPX}(j)_0$, thus avoiding the presence of collinear variables in the final explanatory set. The next steps were performed iteratively, until the predictors added to the model resulted likely to be a meaningful addition, i.e. their p-value was smaller than 0.05. On the kth step, the multivariate regression was performed using $L_{CPX}(j)_0$ and the set of variables $\{VAR_1, \cdots VAR_k\}^k = \{VAR_1, \cdots, VAR_{k-1}\}^{k-1} \cup VAR_k$, where VAR_k was selected by the analysis of the correlation between $L_{CPX}(j)_{k-1}$ and the remaining input parameters, after removing the k-1 variables already selected. This iterative process is shown in the flow chart in Fig. 7.

It is important to emphasize that in each iterative step the multivariate regression was performed using the unmodified wide-band levels $L_{CPX}(j)_0$, in order to avoid the influence of mutual correlation among the set of variables. Lastly, for each $L_{CPX}(j)_0$ a multivariate model was provided:

Table 3
Wide-bands of the two and three band models.

Three-band model	Low frequency					Mid frequency			High frequency				
Central frequency [Hz]	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Two-band model	Low frequency							High frequency					

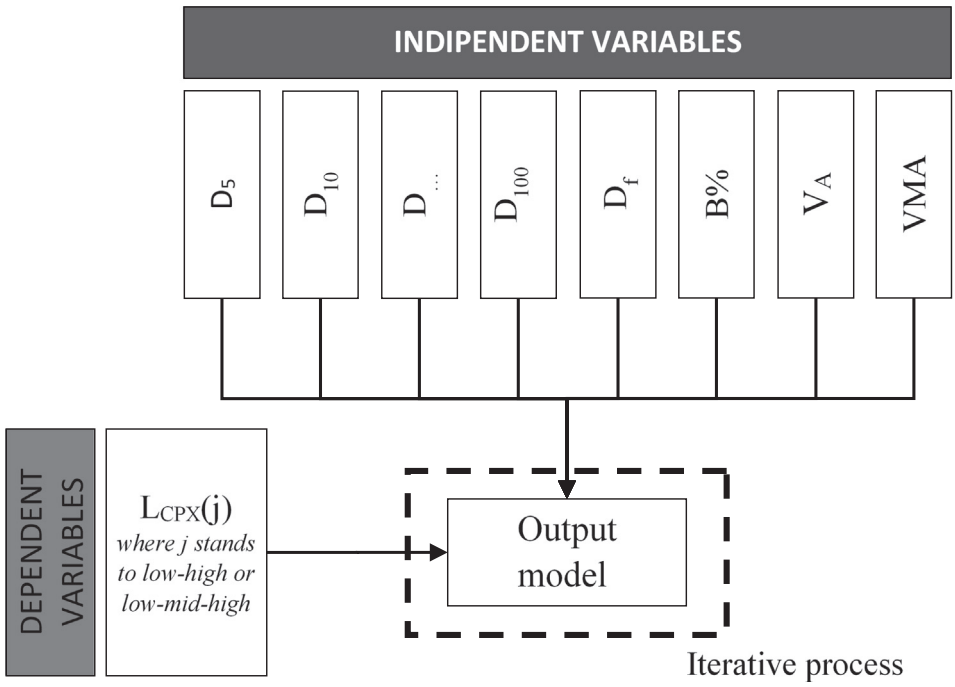

Fig. 6. Flow chart.

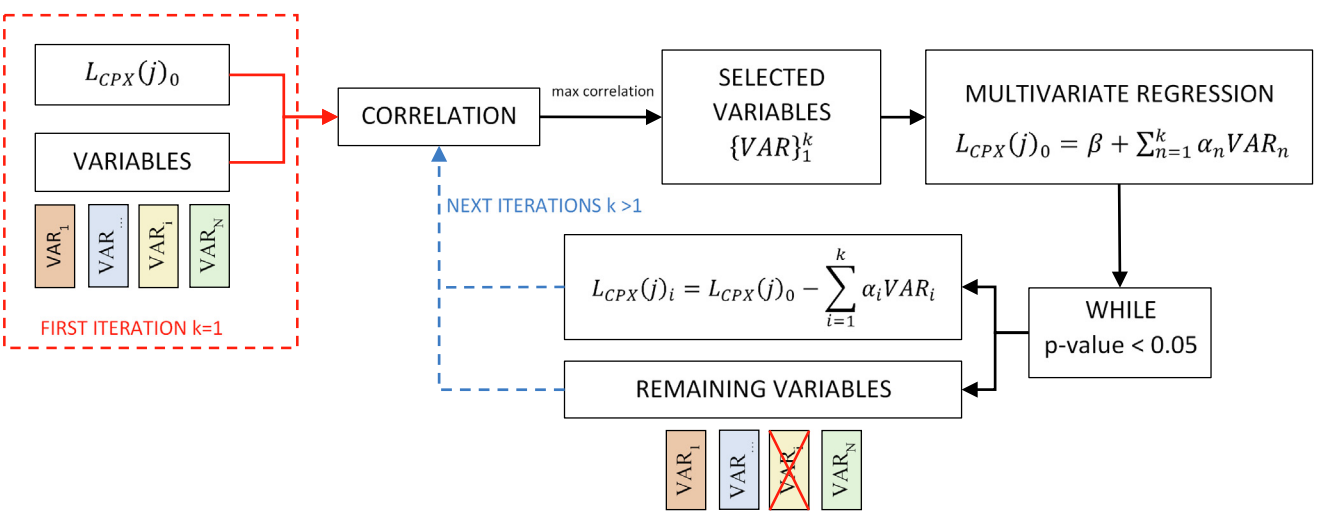

Fig. 7. Stepwise-like regression process.

$$L_{CPX}(j)_0 = \beta + \sum_{n=1}^{k} \alpha_n VAR_n \quad (8)$$

where β is the intercept of the multivariate regression.

5. Results

Using the notation reported in Table 3, two different models were elaborated with different frequency ranges. At the end of the iterative process, the non-collinear set of variables most correlated with each single CPX wide-band levels was found. In particular, for the two-band model, the low frequency region was modelled using a linear combination of asphalt binder content (*B* %), *VMA*, fractal dimension (D_f) and the diameter of 100th percentile passing sieve (D_{100}). The high frequency region showed the highest correlation with fractal dimension (D_f) and the diameter of the 45th percentile passing sieve (D_{45}) and was therefore modelled using these variables.

The three band model uses the D_{95} passing sieve percentage for the low frequency region, instead of the D_{100}, while the high frequency region uses a linear combination of D_f and D_{45}. The remaining mid frequency region was modelled using D_f, D_{45}, *VMA*

Table 4
Significant independent variables.

Two-band model		Three-band model	
Frequency range	Model variables	Frequency range	Model variables
Low (315–1250 Hz)	*B%*, *VMA*, D_f, D_{100}	Low (315–800 Hz)	*B%*, *VMA*, D_f, D_{95}
		Mid (1000–1600 Hz)	*B%*, *VMA*, D_f, D_{45}
High (1600–5000 Hz)	D_f, D_{45}	High(2000–5000 Hz)	D_f, D_{45}

Table 5
Two-band linear regression coefficients. Uncertainties related to the coefficients are estimated through the fitting algorithm and represent the confidence bounds at 95% confidence level.

Low frequency	High Frequency
r^2_{adj} = 0.950	**r^2_{adj} = 0.904**
β_l = 12.16 ± 2.62 dB(A)	β_h = -11.71 ± 3.47 dB(A)
a_{l1} = 0.48 ± 0.12 dB(A)	a_{h1} = 35.44 ± 1.3 dB(A)
a_{l2} = 0.50 ± 0.02 dB(A)	a_{h2} = 2.52 ± 0.13 dB(A)/mm
a_{l3} = 22.21 ± 1.12 dB(A)	–
a_{l4} = 0.42 ± 0.04 dB(A)/mm	–

and $B\%$. Table 4 summarises the independent variables that resulted significant for each band.

6. Two-band model

The two-band model separates the contributions to broadband CPX level into two different frequency regions, modelled as a linear combination of parameters deriving from the job mix formula of the road surface. The linear regression coefficients obtained for Eq. (9) are reported in Table 5.

$$\begin{aligned} L_{CPX}(Low) &= \beta_l + a_{l1}B\% + a_{l2}VMA + a_{l3}D_f + a_{l4}D_{100} \\ L_{CPX}(High) &= \beta_h + a_{h1}D_f + a_{h2}D_{45} \end{aligned} \tag{9}$$

Fig. 8 shows the predicted low frequency, high frequency and reconstructed broadband levels versus the experimental CPX ones. Despite high values of r^2_{adj} were obtained for both regressions, a visual inspection of data in the figure shows that the model developed describes better noise at low frequencies compared to high frequencies, where the presence of two possible outliers, namely id 10 and id 6, could influence the results. This provides further motivation for the development of the three band model. Anyway, experimental and modelled broadband levels are in accordance, as their values lay on the equality line.

7. Three-band model

Since previous studies on correlation between pavement surface properties and rolling noise show poor correlation around 1 kHz [54,55], the three-band model was developed in order to better investigate this region and describe the relation with mixture parameters. The regression coefficients for the three band model shown in Eq. (10) are reported in Table 6.

$$\begin{aligned} L_{CPX}(Low) &= \beta_l + a_{l1}B\% + a_{l2}VMA + a_{l3}D_f + a_{l4}D_{95} \\ L_{CPX}(Mid) &= \beta_m + a_{m1}D_f + a_{m2}D_{45} + a_{m3}VMA + a_{m4}B\% \\ L_{CPX}(High) &= \beta_h + a_{h1}D_f + a_{h2}D_{45} \end{aligned} \tag{10}$$

Fig. 9 shows the predicted low frequency, mid frequency, high frequency and reconstructed broadband levels versus the experimental CPX ones.

8. Discussions

Both models developed show dependence on the fractal dimension D_f for all wide-bands. As far as the diameter percentiles are concerned, lower frequencies are related to larger diameters, such as the D_{100} (two-band model) and the D_{95} (three-band model), while mid-high frequency noise results correlated with the D_{45}. The mid frequency and the low frequency region of the three band model depend on the same set of variables, except for the diameter percentile, which is D_{45} for the mid frequency band. These results are in agreement with studies regarding the relationship between road texture and tyre/road noise [50,51], since low frequency noise results correlated with long texture wavelengths, determined by larger diameter percentiles, and high frequency noise is correlated with shorter wavelengths, that is to say smaller diameter percentiles. However, contrary to the expectations, high frequencies are not dependent on air voids (*VMA* and *VA*).

Table 6
Three-band linear regression coefficients. Uncertainties related to the coefficients are estimated through the fitting algorithm and represent the confidence bounds at 95% confidence level.

Low frequency	Mid Frequency	High Frequency
r^2_{adj} = 0.972	**r^2_{adj} = 0.912**	**r^2_{adj} = 0.851**
β_l = 27.70 ± 1.35 dB(A)	β_m = -10.21 ± 3.17 dB(A)	β_h = -16.19 ± 4.35 dB(A)
a_{l1} = 0.26 ± 0.06 dB(A)	a_{m1} = 30.99 ± 1.44 dB(A)	a_{h1} = 35.86 ± 1.6 dB(A)
a_{l2} = 0.28 ± 0.014 dB(A)	a_{m2} = 1.97 ± 0.20 dB(A)	a_{h2} = 1.96 ± 0.16 dB(A)/mm
a_{l3} = 17.39 ± 0.57 dB(A)	a_{m3} = 0.28 ± 0.05 dB(A)	–
a_{l4} = 0.59 ± 0.028 dB(A)/mm	a_{m4} = 0.69 ± 0.14 dB(A)/mm	–

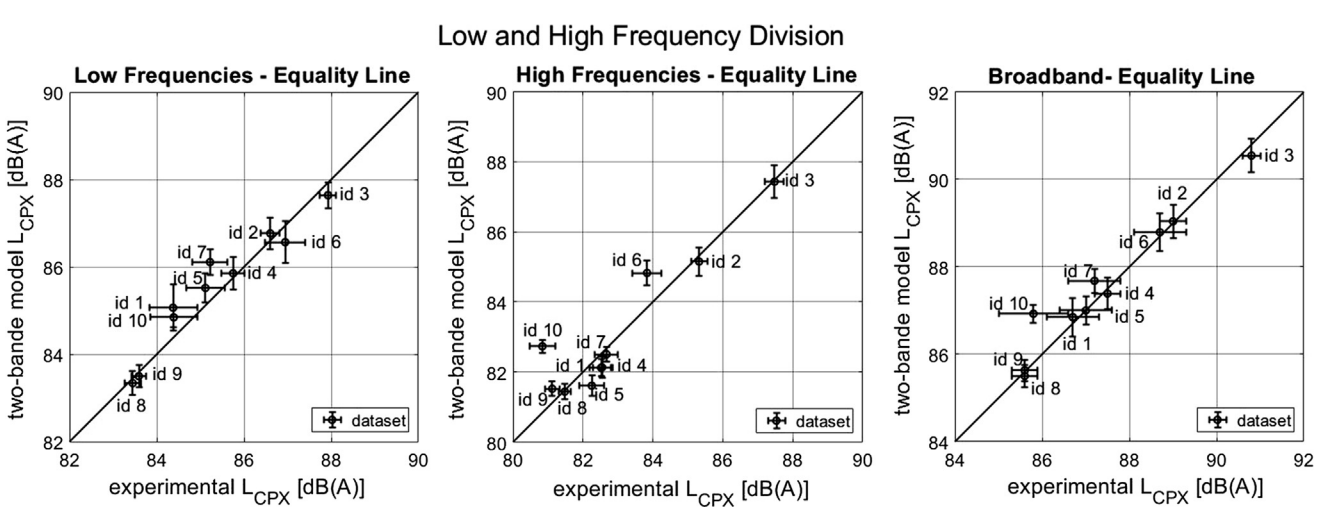

Fig. 8. Predicted vs experimental levels for two-band model.

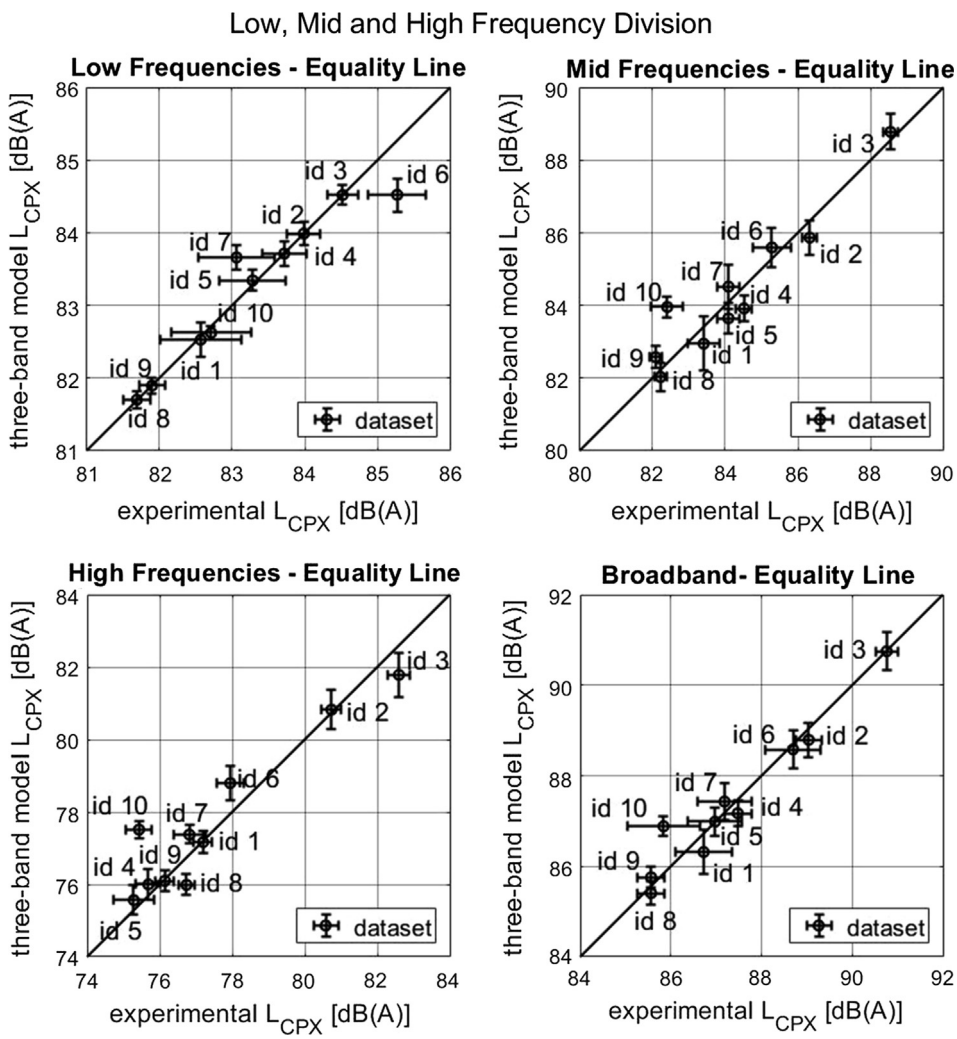

Fig. 9. Predicted vs experimental levels for three-band model.

Table 7
RMSE values for the two models.

Two-band model		Three-band model	
Frequency range	RMSE	Frequency range	RMSE
Broadband L_{CPX}	0.41	Broadband L_{CPX}	0.37
$L_{CPX}(Low)$	0.45	$L_{CPX}(Low)$	0.26
–	–	$L_{CPX}(Mid)$	0.63
$L_{CPX}(High)$	0.75	$L_{CPX}(High)$	0.83

Table 7 shows the RMSE of all linear regressions. The three-band model offers a lower RMSE value for the broadband L_{CPX}, mainly thanks to the significant improvement of the $L_{CPX}(Low)$ prediction. On the other hand, high frequencies do not show a similar improvement switching from the two-band model to the three-band one. Interestingly, the RMSE value for mid frequencies in the three-band model is lower than the high frequencies bands for both models, in spite of results obtained in previous studies which faced serious issues when modelling frequencies around 1 kHz [49,50].

The lower RMSE of the three-band model for the broadband CPX levels could be due to the better description of the different influences of the road mix properties on tyre/road noise at different frequencies, managing to describe the frequency region around 1 kHz where a transition between the two bands occurs. Using a reduced number of subdivisions cannot take into account all the different processes.

Further considerations can be brought about by calculating CPX levels on the two open surfaces using the two models. As shown in Fig. 10, the two-band model does not perform well on these surfaces. The three-band model (Fig. 11), although reaching a better agreement in the broadband evaluation, clearly does not provide an adequate modelling for the wide-band levels on open surfaces. An explanation of this discordance could be provided by the different function of air void content on tyre/road noise emission among dense and open road surfaces, which could not be highlighted by the modelling performed by using only dense surfaces, the most widespread on Italian territory.

The models developed show the possibility of predicting the CPX level in the mix design phase, but further research is needed to decrease variability of volumetric parameters due to testing procedure, whose influence on the measurements has been studied [56–58], and to evaluate the right model coefficients for the new Standard Reference Test Tyre (SRTT) required by the ISO 11819-2:2017 [41]. However, the procedure suggested in the paper is easily applicable when a sufficient number of tests performed using the SRTT will be available.

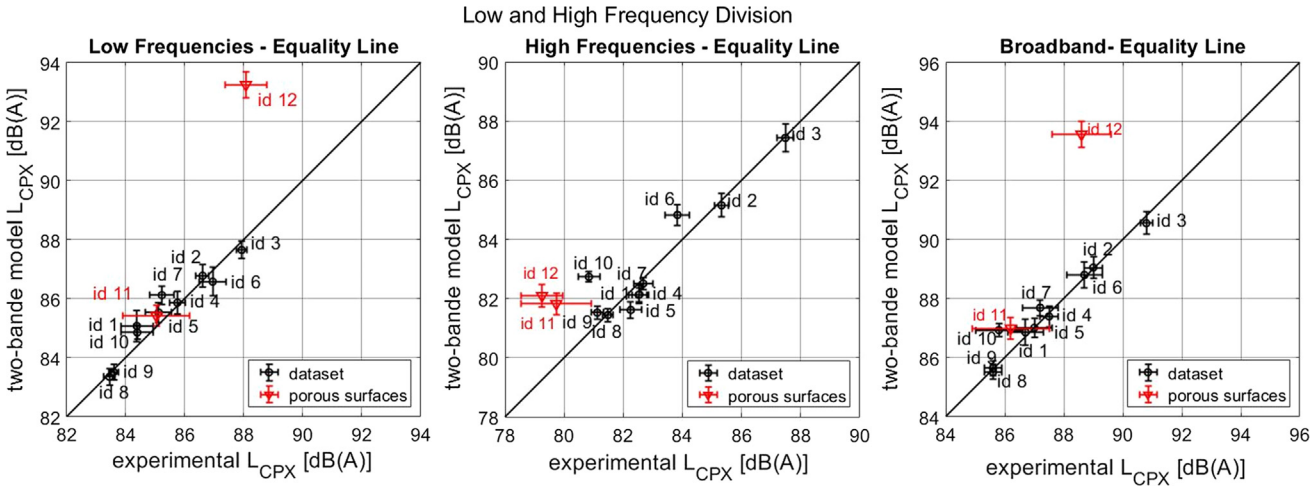

Fig. 10. Comparison of experimental and forecasted values for porous surfaces (two-band).

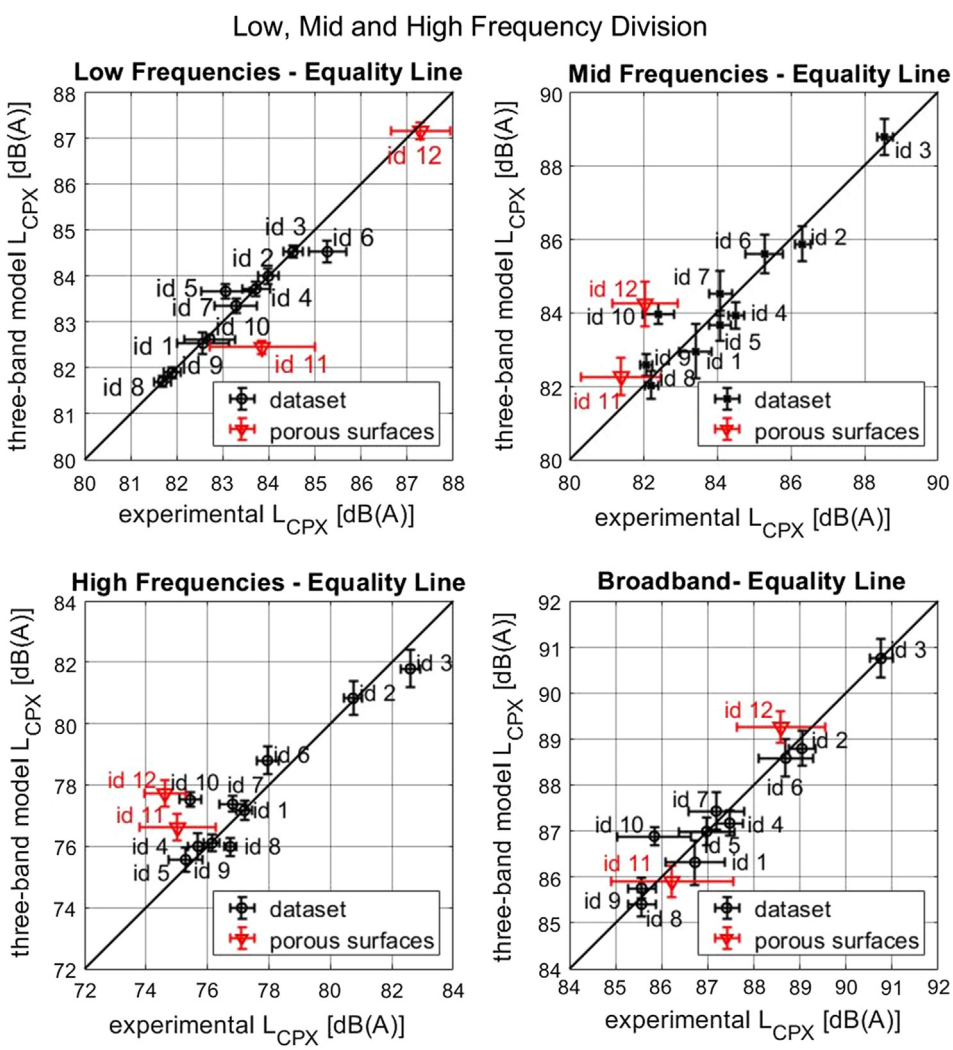

Fig. 11. Comparison of experimental and forecasted values for porous surfaces (three-band).

9. Conclusions

For new low-noise pavements, the European legislation GPP has recently prescribed acoustic tests by means of the CPX method during the first 3 months after laying; therefore, forecasting the acoustic performance of a pavement in terms of the CPX level from the job mix formula now holds an extremely important role, since it could lead to both time and money saving. The objective of this work

was to develop a procedure for the development of a model capable of predicting the initial value of L_{CPX} from the job mix formula.

In particular, the different interaction between road surface properties and noise was considered by splitting the frequency range in wide frequency bands, rather than using broadband levels. The choice of performing a frequency analysis was based also on the knowledge that tyre/road noise exhibits a frequency-dependent behaviour, and therefore, in order to provide a better description of the phenomenon, a broadband description was deemed insufficient.

The dataset was composed by 10 low-noise road surfaces, widespread on the Italian territory, and two open surfaces, which were only used for testing. Using the 10 low-noise road surfaces, two models have been proposed using a stepwise-like regression based on a forward selection, which allows to choose a non-collinear set of explanatory variables well correlated to the CPX levels: the first one uses two wide-bands, while the second one also separates the contribution between 1000 and 1600 Hz in a third band. This range is known to be a transition region between the low frequency and high frequency regions for the correlation between tyre/road noise and road surface properties. Both models developed provide a powerful way to predict the acoustical properties of newly laid low-noise road surfaces, surveyed with a reference tyre different from the standard one (SRTT), however the three-band model showed a lower broadband RMSE. This could be due to a better separation of the various phenomena which occur at the different frequencies involved in CPX measurements: the three-band model, in contrast to the two-band one, presents a mid-frequency region where the transition between vibrodynamic and aerodynamic noise happens.

Analysis of the behaviour of the two models on two open road surfaces available for the study show that these surfaces require a specific modelling of their acoustical behaviour, due to their sound absorption properties. This could be the objective of further research in order to establish a more general model, when more open surfaces will be available for testing.

Lastly, future investigations are required to develop similar models able to predict L_{CPX} using the SRTT, for both open and closed surface families. Indeed, since the approach adopted in this work is general and based on regression and statistical analysis, it could be easily reproduced when the sample size of CPX data compliant with the last ISO release on newly laid surfaces will be sufficiently large. In principle, the use of a different tyre should, result in different regression coefficients, without altering the significant parameters found.

CRediT authorship contribution statement

Luca Teti: Conceptualization, Methodology, Supervision, Writing - review & editing. **Gonzalo de León:** Software, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Alessandro Del Pizzo:** Software, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Antonino Moro:** Investigation, Resources, Writing - review & editing. **Francesco Bianco:** Investigation, Resources, Writing - review & editing. **Luca Fredianelli:** Resources, Writing - original draft, Writing - review & editing. **Gaetano Licitra:** Funding acquisition, Supervision, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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