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MACHINE LEARNING TECHNIQUES FOR TYRE ROLLING NOISE ON RUBBERIZED ASPHALT ROADS

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ABSTRACT

Tyre rolling noise remains a significant contributor to overall noise pollution, characterizing also electric vehicle emissions for speed greater than 25 km/h. Among low-noise pavements, rubberized asphalt roads have gained widespread use due to their acoustic benefits and durability over time. Additionally, these pavements provide an effective solution for recycling End-of-Life Tyres (ELTs), a challenging waste product to manage, which stockpiling poses substantial environmental risks, including fire hazards and serving as breeding grounds for disease-carrying mosquitos. In this work, Machine Learning techniques will be employed to evaluate and characterize various aspects of the investigated pavements, with a particular focus on those incorporating crumb rubber particles inserted with the Dry or Wet process. The pavements acoustic emission, measured using the standardized Close ProXimity (CPX) method, as well as through their texture profile, were collected. The pavements under investigation were geographically distributed across different regions of Italy, exposing them to varying external factors. The goal of this research project is to develop an artificial intelligence tool capable to improve the pavement design.

Keywords: *TRN, CPX, Rubberized surfaces, Machine learning, Acoustic ageing*

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1. INTRODUCTION

As Tyre Rolling Noise (TRN) remains a significant contributor to overall noise pollution [1], studies on the modeling of the source and the finding of innovative low-noise pavements are still a central theme. Among low-noise pavements, rubberized asphalt surfaces have gained widespread use due to their acoustic benefits and durability over time [2]. Their different relationship with respect to pavement texture has been the object of a study [3] that shows a different cross-over frequency between structure-borne and air-borne TRN mechanisms. At the same time, studies on the acoustical ageing of pavements based on the traffic load and climatic conditions show that each pavement has its particular acoustic durability [4].

In this work, pavements containing and not containing crumb rubber of End-of-Life Tyres are analyzed with the use of the Support Vector Regressor (SVR) algorithm. The selection of the SVR has been done in the light of the good results found in [5] where the authors have been able to predict CPX broadband levels in function of the air temperature, texture properties and aggregate compositions. In this study, investigated surfaces involved both pavements realized with the Dry and the Wet procedure. All pavements in this study are usually classified as dense surfaces. The dataset includes pavements located at different sites in Italy, where repeated measurements of TRN using the Close ProXimity method and road texture have been carried out over time to evaluate their acoustic durability. In specific, in this work the SVR algorithm with a Radial Basis Function (RBF) kernel is used to predict the TRN one-third octave band emission. In a first moment, the pavements are characterized by their texture profile and the presence or not of crumb rubber with distinction between Dry and Wet processes. Not pavement related input parameters to the model have been the mean air temperature during the measurements and the hardness of the reference tyre measured in laboratory conditions. This first step aims to highlight possible differences in the acoustic emission of pavements due to the presence of crumb-rubber, excluding the texture influence. In a second step, the dataset has been reduced to pavements of a same site to ensure equal traffic load and climatic conditions. The pavements taken for the analysis involved a Dry pavement, a Wet pavement, a texture-optimized pavement and a traditional pavement. The results of this second step focus on the acoustic performance evalution over time of the pavements.

2. EXPERIMENTAL SETUP

Measurements of TRN were carried out using the standardized CPX configuration [6]. CPX one-third octave band and broadband levels were estimated at a reference speed of 50 km/h on 20 m long pavement segments.

Texture measurements were performed using a laser profilometer with a spot size of 0.13 mm. Profile measurements, taken at 30 km/h, were selected to represent the pavement surfaces. For each 20 m long segment, the texture wavelength spectrum, from 1.25 mm up to 500 mm, spectrum was measured.

Air temperature was measured during each measurement. The mean air temperature was used in this analysis. Tyre hardness was been measured in laboratory at the reference temperature of $20°C$ before the measurements.

3. MACHINE LEARNING AND SUPPORT VECTOR REGRESSOR

The Support Vector Machine (SVM) was originally developed for binary classification tasks. Its core principle involves defining a hyperplane that separates data points into two classes by maximizing the margin between them. The SVR, on the other hand, extends this concept to regression problems by defining a hyperplane that best fits the observed data within a specified maximum error margin [7].

One way to introduce non-linearity in the problem and optimize problem solution finding is through the use of the kernel trick. In this work, the SVR algorithm is implemented with the scikit-learn Python library [8]. In this work the RBF, defined in Eq.(1), has been selected.

$$k(x_i, x_j) = exp(-\frac{d(x_i, x_j)^2}{2l^2}) \quad (1)$$

In Eq.(1) l is the length scale of the kernel, d the euclidean distance between the points and x_i the feature element. The selected parameters for the model are reported in Tab. 1.

Table 1. SVR parameters

Parameter	selection
kernel	radial basis function (rbf)
C	10
ϵ	0.1

In the table, C represents the inverse of the regularization factor in the algorithm's loss function, which in this work is defined using the root-mean-square error. Finally, ϵ refers to the epsilon parameter in the epsilon-SVR model. It defines the epsilon-tube, within which no penalty is applied in the training loss function for points predicted within a distance ϵ from the actual target value. In a first step the data was used without the addition of the pavement age while a second step focused in the ageing prediction for pavements in a specific location.

4. RESULTS

In the following study, the dataset has been divided into 40% for training and 60% for testing. The pavement typology was included with a one-hot encoding:

- 0 if the crumb rubber has been added with the Dry process;
- 1 if the crumb rubber has been added with the Wet process;
- 2 if no crumb rubber has been added (ST, Standard Typology);

4.1 Parameters influence and CPX distributions

For each CPX one-third octave band frequency, the SVR algorithm was applied to build a separate predictive model. Tab. 2 reports the final R^2 and R^2_{adj} of the predictive models.

To visualize the effect of crumb rubber insertion, predictions were made by fixing the air temperature at $20°C$,

Table 2. R^2 and R^2_{adj} for the SVR model

Frequency [Hz]	$\mathbf{R^2}$	$\mathbf{R^2_{adj}}$
315	0.81	0.79
400	0.81	0.80
500	0.77	0.76
630	0.85	0.84
800	0.81	0.81
1k	0.80	0.79
1.25k	0.80	0.79
1.6k	0.77	0.76
2k	0.79	0.78
2.5k	0.79	0.78
3.15k	0.77	0.76
4k	0.76	0.75
5k	0.78	0.77

tyre hardness 66 ShoreA, while evaluating the model prediction across all texture pavement segments in the dataset. In particular, Fig. 1 shows the resulting distribtuion of CPX broadband levels. Tab. 3 reports the mean value of the distributions and the standard deviation of the distributions.

The effect of tyre hardness and air temperature on the TRN emission spectrum were evaluated with predictions on a Dry pavement with a fixed texture profile. Variations were introduced by fixing independently the air temperature or the tyre hardness. Fig. 2 shows the variation in the one-third octave band spectrum due to the change in tyre hardness, while Fig. 3 represents the influence of air temperature. To study the effects of air temperature on different pavement types, the CPX A-weighted broadband levels were computed using a fixed pavement texture profile and a tyre hardness value, while varying both pavement type and temperature. The results are presented in Fig. 4. Finally, the interaction between tyre hardness and air temperature is illustrated in Fig. 5, where the pavement composition was set to Dry, the texture profile was fixed, and both temperature and tyre hardness were varied.

Table 3. Predicted CPX broadband levels

Type	$\overline{\mathbf{L_{CPX}}}$	$\sigma\mathbf{L_{CPX}}$
Dry	91.21 dB(A)	0.95 dB(A)
Wet	91.27 dB(A)	0.90 dB(A)
ST	91.38 dB(A)	0.81 dB(A)

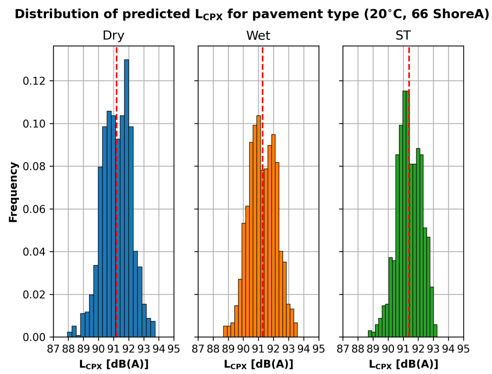

Figure 1. CPX predicted broadband levels

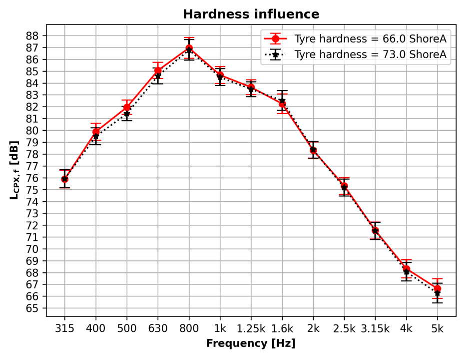

Figure 2. Tyre hardness influence spectrum for a Dry pavement at 50 km/h.

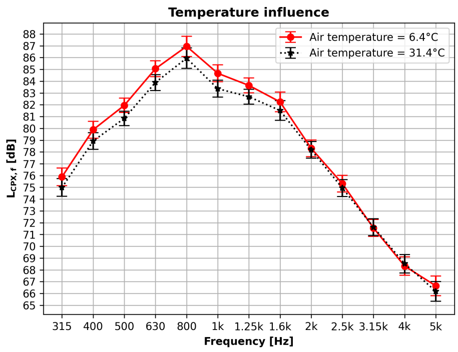

Figure 3. Air temperature spectrum influence for a Dry pavement at 50 km/h.

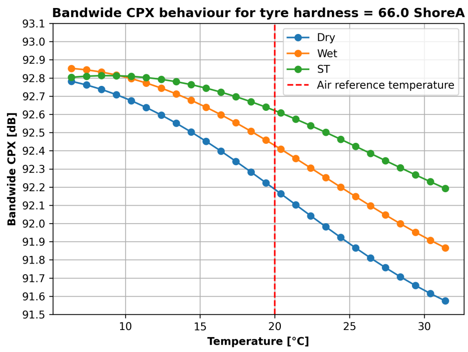

Figure 4. CPX level behaviour at different temperature, same texture, hardness but different materials.

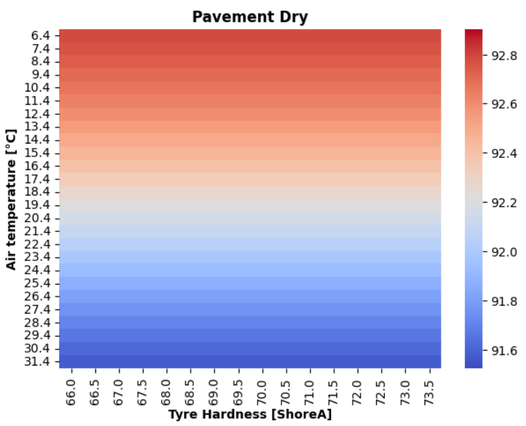

Figure 5. Dry pavement CPX broadband levels in function of tyre hardness and air temperature.

4.2 Pavement acoustic ageing

In this second step of the analysis the dataset was reduced to four pavement types, all measured at the same site. The pavements under investigation were: a Dry pavement; a Wet pavement; a texture-optimized pavement and a traditional pavement (for the ST typology). Fig. 6 shows the mean CPX broadband levels measured during the experimental campaigns in function of their age. The results of the SVR model, incorporating pavement age as an input, are reported in Tab. 4. Fig. 7 shows the predicted CPX broadband levels as a function of pavement type and age, with fixed texture profile, tyre hardness, and air temperature.

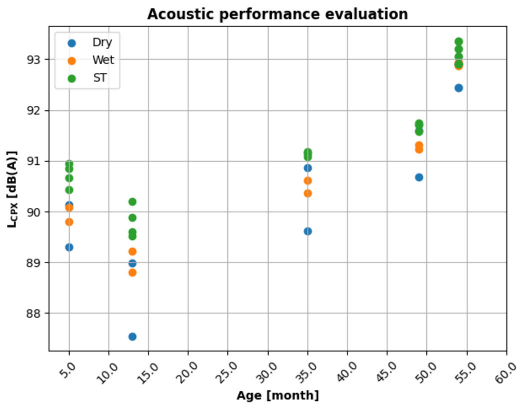

Figure 6. CPX broadband levels in time.

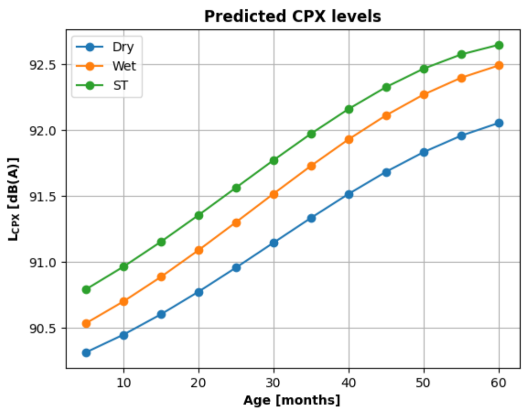

Figure 7. Predicted pavements CPX levels at 50 km/h over time.

Table 4. R^2 and R^2_{adj} for the SVR model

Frequency [Hz]	$\mathbf{R^2}$	$\mathbf{R^2_{adj}}$
315	0.39	0.35
400	0.64	0.62
500	0.83	0.82
630	0.87	0.87
800	0.88	0.87
1k	0.87	0.86
1.25k	0.89	0.89
1.6k	0.85	0.84
2k	0.86	0.85
2.5k	0.89	0.88
3.15k	0.86	0.85
4k	0.89	0.88
5k	0.89	0.89

5. DISCUSSIONS

Tab. 2 shows that the SVR algortihm correctly models the CPX one-third octave spectrum with a minimum R^2 value equal to 0.76 for the 4 kHz frequency. Distribution of the predicted CPX broadband levels, presented in Fig. 1, does not reveal a clear distinction based on pavement type confirmed by the values reported in Tab. 3. Fig. 2, Fig. 3 and Fig. 5 illustrate the influence of tyre hardness and air temperature on the prediction models for the Dry pavement type. The results highlight that air temperature is the dominant factor affecting the spectral emission, while no significant interaction is observed between tyre hardness and air temperature. Finally, Fig. 4 shows how CPX broadband levels vary with air temperature across different pavement types. Not all pavements exhibit a linear relationship with temperature within the selected range.In the second phase, the initial distribution of mean CPX broadband levels per pavement type and surface, shown in Fig. 6, indicates an initial acoustic benefit that degrades over time. Tab. 4 highlights the complexity of SVR prediction in the low-frequency region for the selected site. Finally, Fig. 7 illustrates the influence of pavement age on the model when the texture profile is excluded. The predicted CPX broadband levels for the Wet and St pavements exhibit similar trends, whereas the Dry pavement shows a less steep degradation over time.

6. CONCLUSIONS

In conclusion, this work demonstrates the applicability of the SVR algorithm with the RBF kernel for studying and predicting TRN across different pavement types. When applied to the full dataset without considering pavement age, the SVR model effectively predicted the CPX one-third octave band levels across all frequencies. The results suggest a relationship between air temperature and pavement type. Variations in the pavement properties appear to play a role in TRN, highliting the need to incorporate additional pavement related parameters. Furthemore, the findings indicate that Dry pavements exhibit greate acoustic durability compard to both non-crumb rubberized pavements and Wet pavements. Future research will focus on integrating additional pavement characteristics, such as porosity and pavement stiffness, and further studies on the SVR to better comprehend the relationship between the different inputs.

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