Acoustical characterization of low-noise prototype asphalt concretes for electric vehicles

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Abstract

The paper deals with the acoustical characterization of low-noise asphalt concretes developed for noise reduction in urban areas within the LIFE E-VIA project (LIFE18 ENV/IT/000201). With the perspective of an increasing number of electric vehicles (EVs) in urban area, the asphalt concrete mixes have been optimized considering Life Cycle Cost with respect to actual best practices. Two very thin asphalt concretes (VTAC) of 6 mm maximum aggregate size have been implemented on a reference test track in France. Both are based on the same formulation, but one mix contains 1.9% crumb rubber by weight. The noise performance of these prototype test sections has been evaluated by means of close-proximity (CPX) tests and controlled pass-by (CPB) noise measurements for two EV models. CPX results have shown a noise reduction of about 3 dB(A) by comparison with a reference dense asphalt concrete 0/10, while an average pass-by noise reduction of about 4 dB(A) has been observed for the sample of EVs tested.

Keywords: electric vehicles noise, tyre/road noise, low-noise asphalt concrete, life cycle analysis.

1 Introduction

According to recent data of European Alternative Fuel Observatory (EAFO), the electric vehicle (EV) fleet in the European area is growing exponentially, reaching 3.1 million of EVs in 2020 and 10.7% of market share new registrations [1]. The different projection scenarios proposed in [2] expect EVs to represent between 15% and 30% of the global vehicle fleet by 2030, reaching between 130 and 250 million vehicles worldwide.

In this context, considering the relative quietness of electric motors, rolling noise is likely to become the prominent source of noise in urban area from about 20 km/h at constant speed [3]. Therefore, one of the main objectives of the European LIFE E-VIA project [4] is the reduction of tyre/road noise by proper optimization of the tyre/road interaction. A literature review has shown that EV tyres are not necessarily the quietest [5]. Apart from some specific EV model, the future market of EV tyres will also stay within standard tyre dimensions [6], while EVs have some specificities by comparison with intern combustion engine vehicles (ICEV) such as higher torque and curb weight. According to [7], EVs noise abatement could highly benefit from low-noise road surfaces, with a possible stake in noise reduction of at least 6 dB(A) on the average EV fleet.

This study deals with the acoustical characterization of low-noise very thin asphalt concretes developed for noise reduction in urban areas within the framework of the LIFE E-VIA project. The asphalt concrete mixes have been developed considering Life Cycle Analysis (LCA) as e.g. [8] in the perspective of an increasing number of EVs in urban area. The first section of this article describes the mix design procedure and the implementation of two low-noise prototypal asphalt concretes, as well as road surface properties influencing tyre/road noise (i.e. surface texture, sound absorption and dynamic stiffness). Then, the acoustical characterization of the prototype test sections is presented. It relies on close-proximity (CPX) and controlled pass-by (CPB) measurements. The results are given and discussed at the reference speed of 50 km/h. The last section gives the main conclusions and outlook of the study.

2 Low-noise asphalt concrete for electric vehicles

2.1 Holistic optimization of the mix

The framework of the study carried out to optimize the low-noise asphalt concrete mixtures, which are the main outputs of the LIFE E-VIA Project, are described in the following. In particular, the study consisted of 3 main tasks (see Figure 1) that were organized as follows:

TASK 1.1: A comprehensive literature analysis [9-11], which allowed finding 150 asphalt concrete mixtures, was carried out (Actor: University MEDITERRANEA of Reggio Calabria, UNIRC; Project Action: A2).

TASK 1.2: From the 150 asphalt concrete mixtures above, nine mixtures were selected based on many characteristics, including: 1) Acoustic response. 2) Expected life by referring to mechanistic properties. 3) Permeability. 4) Friction (i.e., Mean Profile Depth, MPD, and British Pendulum Number, BPN now PTV). 5) Expected life. 6) ENDT value. Based on the characteristics above, the open asphalt concrete mixture with Nominal Maximum Aggregate of 6 mm (AC6*) was selected as the best low-noise mixture (Actor: UNIRC; Project Action: B1.2).

TASK 2.1: Acoustical and mechanical properties of different reference road pavements in Nantes (France) were measured on site, in order to gather data to use in the next sub-tasks (Actors: Univ. Eiffel and IPOOL; Project Actions: B1.3 and B1.4).

TASK 2.2: Based on the results of the sub-tasks 1.1-2.1, two mixtures were designed, namely two AC6 ones (where AC stands for asphalt concrete and 6 for nominal maximum aggregate size of 6mm). The first one (AC6P) without crumb rubber and the second one (AC6PCR) with crumb rubber (see Table 1). Physical-based models were set up and implemented at the MEDITERRANEA to investigate the interaction among the predicted characteristics. Two pavement prototypes were built (see Figure 3, P and PCR, respectively) and tested on site (see Sections 2.3-3.2) in order to find the correlation and the relationship between the mixtures defined in the laboratory (Sub-task 1.1) and those used to build the prototypes P and PCR (Actors: Univ. Eiffel and IPOOL; Project Action: B2).

TASK 3.1: Based on all the results collected during the tasks above, the final two mixtures were designed (Actor: UNIRC; Project Action: B1.5).

TASK 3.2: The two final mixtures designed in the previous sub-tasks were built in a pilot area (Actor: Municipality of Florence; Project Action: B3). Tests are going to be carried out (by the end of the 2021) to validate the aforementioned mixtures from a mechanical and acoustical point of view.

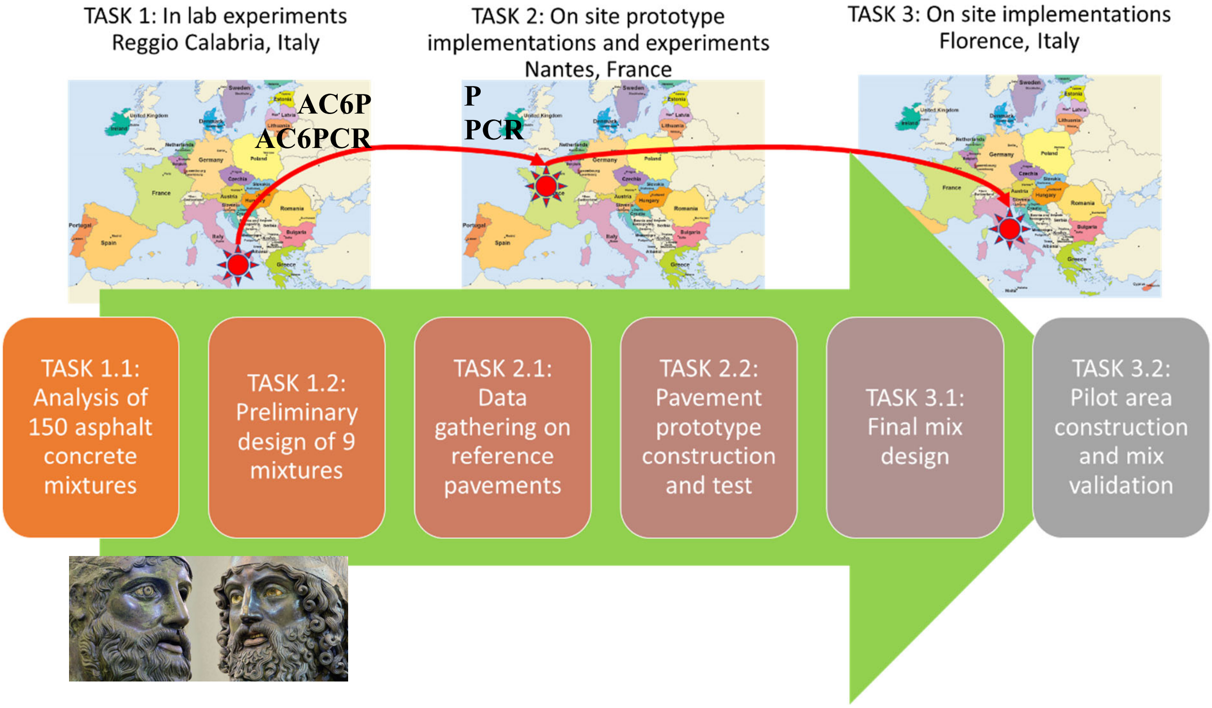

Figure 1 – Framework of the low-noise asphalt concrete mixtures holistic optimization

2.2 Prototype implementation

Based on the conclusions of the holistic approach, two VTAC test sections were implemented in September 2020 on Université Gustave Eiffel reference test track in Nantes (France). Table 1 details each mix composition. Both mixes have a maximum aggregate size of 6 mm. They are based on the same formulation, but one mix contains 1.9% crumb rubber (CR) by weight.

Table 1 – Mix composition of the implemented prototype VTAC 0/6.

Fraction (mm)	Mix without crumb rubber	Mix with crumb rubber
4/6.3	7.0%	7.0%
2/4	33.0%	33.0%
0/2	52.0%	51.0%
0/1 (CR)	-	1.9%
Fines	1.6%	1.0%
Filler bitumen	-	6.1%
Total bitumen	6.4%	6.4%

Figure 2 shows a top view picture of the VTAC 0/6 test sections after implantation. The prototype dimensions were 8 m width by 57 m length. The thickness of the compacted mixture was 0.025 m. The test section without CR was named P, while the one with CR was named PCR.

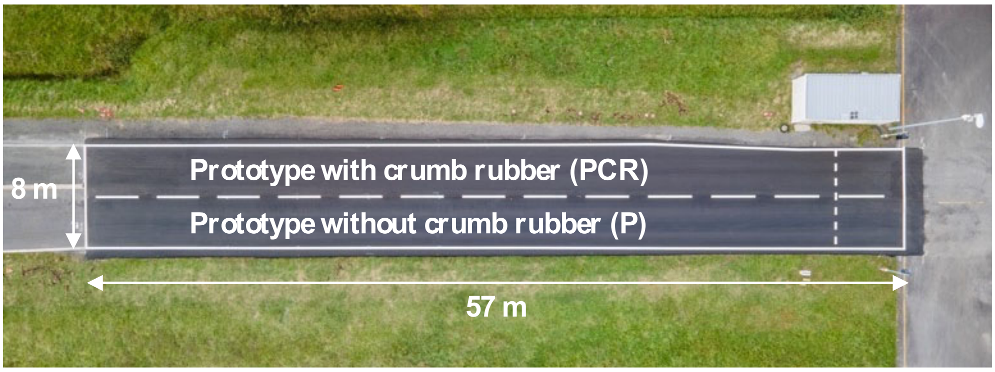

Figure 2 – Top view of VTAC 0/6 test sections built on Univ. Gustave Eiffel test track in Nantes (France).

Figure 3 gives a close-up picture of the VTAC 0/6 test sections and of test section E1 from the same site, which is considered as a reference dense asphalt concrete (DAC) 0/10 within this study. By comparison with E1, the finer grading and the flattening of aggregates for P and PCR can be appreciated on the picture.

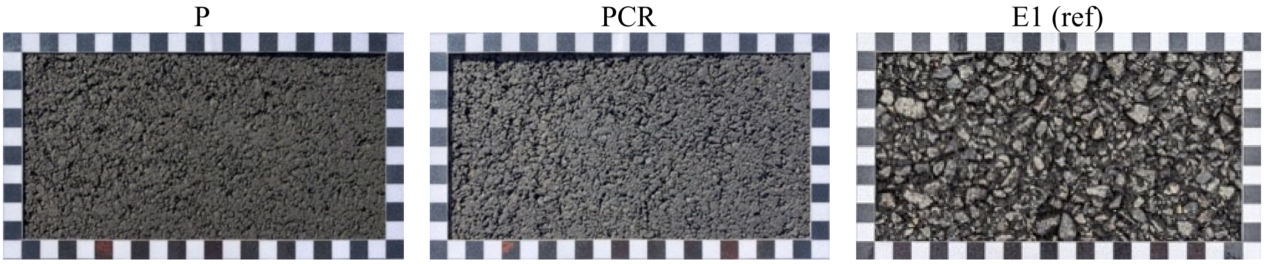

Figure 3 – Close-up pictures (20 cm by 10 cm frame) of test sections P, PCR and E1 (reference DAC 0/10).

2.3 Characterization of road surface properties

2.3.1 Surface texture

Surface texture was measured with a 3D profilometer based on a 2D laser sensor that is moved over the road surface (Figure 4, left). The system allows 3D measurements of length 1.5 m and width up to 0.35 m. Four consecutive scans were performed on the wheel path on the side of the pass-by microphone position and two consecutive scans were carried out on the opposite wheel path. The final complete texture scans were respectively about 5.80 m and 2.94 m long. The longitudinal and transverse sampling intervals were 0.1 mm.

The Mean Profil Depth (MPD) and the texture spectra were calculated using longitudinal profiles extracted from the 3D texture scans, according to respectively ISO 13473-1 and ISO 13473-4. The average MPD was respectively 0.39 mm and 0.30 mm for P and PCR test sections, while 0.82 mm for the reference test section E1. Figure 4 (right) gives one-third octave band texture spectra averaged over the left and right wheel tracks of both prototypal test sections P and PCR. Texture spectrum of E1 is also plotted. The texture levels of section P are up to 3 dB higher than those of section PCR at wavelengths lower than 125 mm, with an opposite situation at wavelengths greater than 250 mm. A peak at wavelength 160 mm is observed for PCR test section. Texture levels of both prototype test sections are much lower than the reference E1, especially at wavelengths higher than 16 mm for which a difference of about 6 dB to 9 dB is observed respectively for P and PCR.

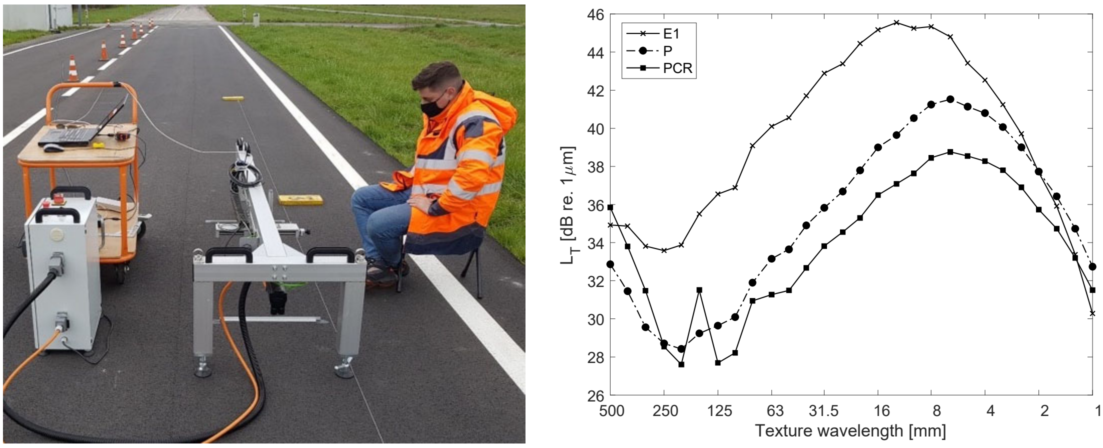

Figure 4 – 3D profilometer (left) and surface texture spectra measured on the 3 test sections (right).

2.3.2 Sound absorption

Sound absorption was measured on test sections P and PCR by means of a system conforming ISO 13472-1 (Figure 5, left). The absorption coefficient was measured in the middle of the test section at five spots located approximately in front of the pass-by microphone and averaged in the narrow bandwidth frequency domain. Then, the sound absorption coefficient was calculated in one-third octave band (Figure 5, right). The sound absorption coefficient was quite low for both prototype test sections, with a maximum value of 0.17 and 0.26 at 2500 Hz for PCR and P respectively.

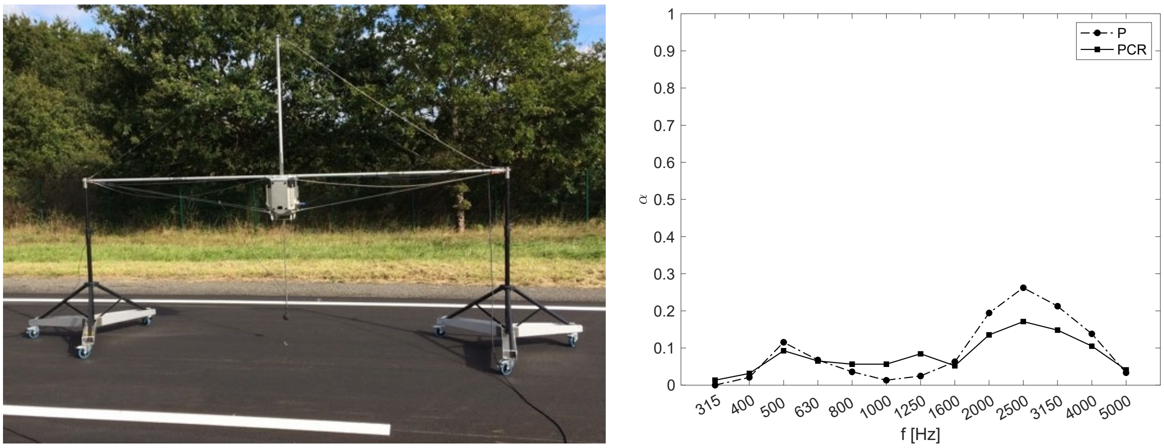

Figure 5 – Sound absorption measurement system (left) and sound absorption coefficient in one-third octave bands (right) measured on prototype road surfaces P and PCR.

2.3.3 Dynamic stiffness

The dynamic stiffness of the prototype test sections was measured *in situ*. The experimental setup is based on the frequency response function between an impact hammer and an impedance head measuring the direct force and acceleration at the impact spot (Figure 6, left). Five different spots were tested, located in the middle of the test section, at the same position as for sound absorption measurements. Figure 6 (right) shows the dynamic stiffness of test sections P and PCR in the frequency range between 100 Hz and 2000 Hz. The dynamic stiffness is almost constant over this frequency range, thus corresponding to an ideal spring behaviour. Although comprising crumb rubber, it is observed that PCR test section is stiffer than P test section, with a difference up to 5 dB below 400 Hz and about 2 dB above 400 Hz.

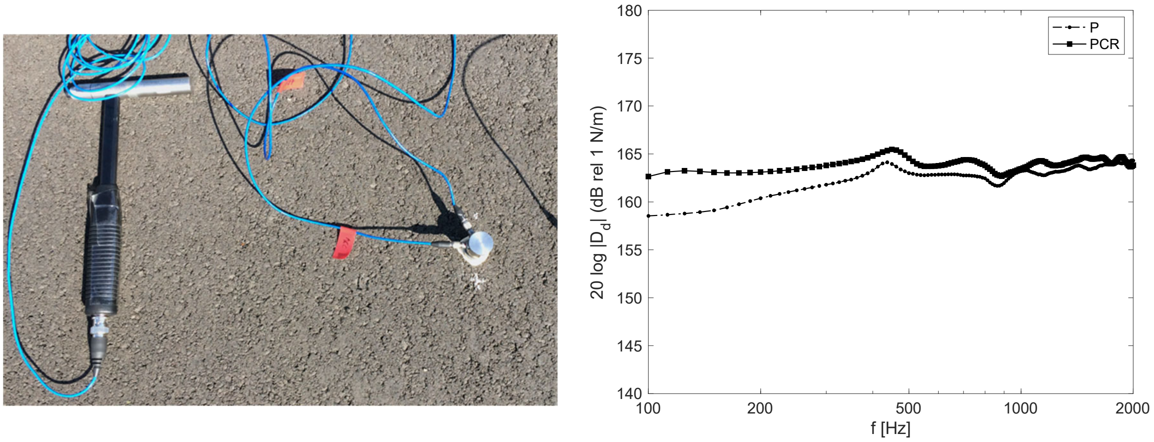

Figure 6 – Impact hammer and impedance head used for the dynamic stiffness measurements (left) and dynamic stiffness as a function of frequency for P and PCR test sections (right).

3 Acoustical characterization of the prototype test sections

3.1 Close-ProXimity measurements

CPX measurements were performed according to ISO 11819-2. Two different test vehicles fitted with different tyre models have been used. The first test vehicle was a passenger car Renault Scénic 2.0 litres fitted with standard commercial tyres Michelin Energy Saver 195/60 R15 (Figure 7, left). The second test vehicle was a Mercedes Vito fitted with SRTT P225/60 R16 according to ISO 11819-3 (Figure 7, right).

On each test section, several runs were performed every 5 km/h at steady speed V from 30 km/h to 110 km/h. For each run, the energetic average of one-third octave band noise levels on lateral microphone was calculated and averaged over the test section. Then, the overall CPX noise level was recomposed from the frequency range between 400 Hz and 4000 Hz for the Michelin tyres and between 315 Hz and 5000 Hz for the SRTT tyres. Finally, a logarithmic regression versus speed was performed on recomposed CPX overall noise levels and for each one-third octave band noise levels to get overall noise levels and spectra at 50 km/h.

Figure 7 – CPX test vehicles: Renault Scénic fitted with Michelin Energy Saver tyres (left) and Mercedes Vito fitted with SRTT tyres (right).

Table 2 gives the regressed CPX overall noise levels at the reference speed of 50 km/h. The noise levels have been corrected in temperature at 20°C for both tyre models and in hardness for the SRTT tyre. For the Michelin tyre, the noise reduction at 50 km/h by comparison with the reference surface E1 is 2.8 dB(A) for P and 2.4 dB(A) for PCR. For the SRTT tyre, the noise reduction is 1.7 dB(A) for P and 2.4 dB(A) for P.

Table 2 – CPX overall noise levels at the reference speed of 50 km/h.

	E1	P	PCR
Michelin Energy Saver 195/60 R15	87.0 dB(A)	84.2 dB(A)	84.6 dB(A)
SRTT P225/60 R16	90.2 dB(A)	88.5 dB(A)	87.8 dB(A)

CPX noise spectra are given in Figure 8 for the three test sections E1, P and PCR and for both tested tyre models. No temperature correction has been applied to spectral noise levels. Both prototype test sections P and PCR have very similar spectral shapes for both tyre models. The maximum spectral value for P and PCR is observed at 800 Hz for the Michelin tyres and at 630 Hz for the SRTT tyres. By comparison with E1, the highest noise reduction is obtained in the frequency range between 800 Hz and 2000 Hz, with a maximum of about 4 dB(A) at 1000 Hz.

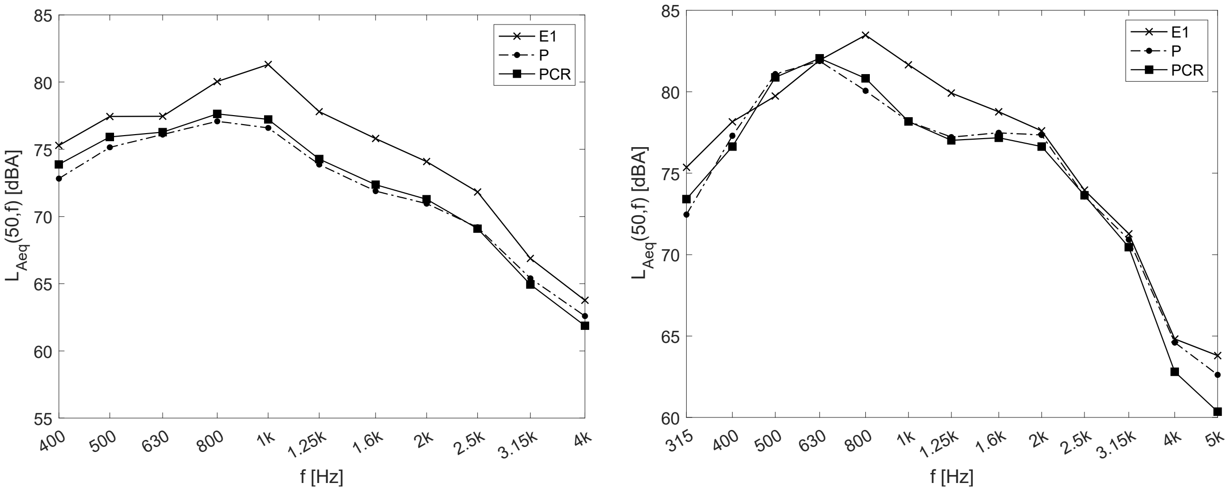

Figure 8 – CPX noise spectra for the Michelin Energy Saver 195/60 R15 tyre (left) and for the SRTT P225/60 R16 tyre (right) at the reference speed of 50 km/h.

3.2 EVs pass-by noise measurements

CPB noise measurements were performed with a microphone located on the left side of the vehicle, at 7.5 m from the middle of the test section and 1.2 m above the road surface. Two EV models were tested (Figure 9): a passenger car Renault ZOE fitted with Michelin Energy EV tyres of size 185/65 R15 and a light commercial vehicle Renault KANGOO Z.E. fitted with Michelin Energy Saver tyres of size 195/65 R15, which have the highest market share in European Union over the last 3 years, respectively for passenger and light commercial EVs [1].

On each test section, several runs were performed every 5 km/h at steady speed V from 20 km/h to 70 km/h. At low speed, the acoustic alerting vehicle system (AVAS) was deactivated. For each run, the maximum overall A-weighted sound pressure level L_{Amax} was identified from the *Fast* time signature and a correction of the background noise level was applied to the overall and spectral noise levels according to a procedure explained in [7]. Then, a logarithmic regression versus speed was performed on CPB overall noise levels and for each one-third octave band noise levels in the frequency range between 100 Hz and 5000 Hz.

Figure 9 – Two tested EV models: Renault ZOE fitted with Michelin Energy EV 185/65 R15 tyres (left) and Renault KANGOO Z.E. fitted with Michelin Energy Saver 195/65 R15 tyres (right).

Table 3 gives the regressed CPB overall noise levels at the reference speed of 50 km/h. The noise levels have been corrected in temperature at 20°C according to [12]. The noise reduction at 50 km/h by comparison with the reference surface E1 is 4.2 dB(A) for PCR and 4.6 dB(A) for P in the case of the Renault ZOE, and 3.9 dB(A) for PCR and 4.5 dB(A) for P in the case of the Renault KANGOO Z.E. It is observed that the Renault KANGOO Z.E. is about 1.5 dB(A) quieter than the Renault ZOE.

Table 3 – CPB overall noise levels at the reference speed of 50 km/h.

	E1	P	PCR
Renault ZOE	67.3 dB(A)	62.7 dB(A)	63.1 dB(A)
Renault KANGOO Z.E.	65.7 dB(A)	61.2 dB(A)	61.8 dB(A)

CPB noise spectra are given in Figure 10 for the three test sections E1, P and PCR and for both EVs. No temperature correction has been applied to spectral noise levels. For both tested vehicles, noise spectra have a similar shape on the reference test section E1, with a clear peak at 1000 Hz. On prototype test sections, this peak is attenuated by 5 dB(A) for the Renault ZOE and the maximum is shifted at 800 Hz on PCR test section. For the Renault KANGOO Z.E., the peak at 1000 Hz is reduced by 10 dB(A) and the maximum is shifted at 630 Hz for both P and PCR test sections. For this vehicle, a peak at 1250 Hz can be observed, but originating from another source than tyre/road noise. For the Renault ZOE, a clear peak is also observed at 315 Hz and is reduced by about 5 to 6 dB(A) on the prototype test sections. While having similar spectral shapes, it is clearly observed for both EVs that noise levels on PCR are slightly higher than noise levels on P in the frequency range between 500 Hz and 1000 Hz, while the opposite is found in the frequency range above 1250 Hz.

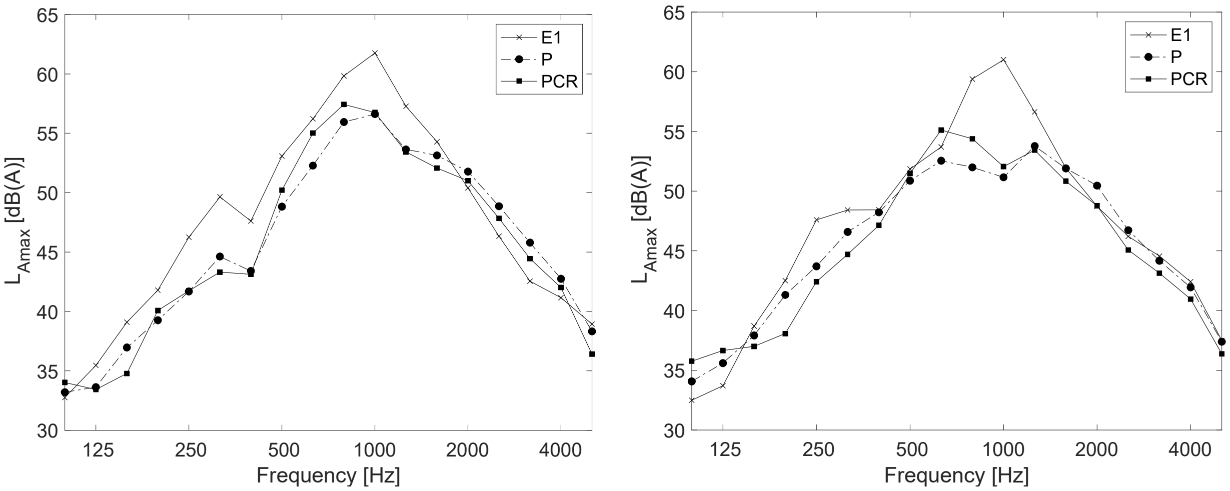

Figure 10 – CPB noise spectra for the Renault ZOE (left) and for the Renault KANGOO Z.E. (right).

3.3 Discussion

CPX and CPB results have shown a significant overall noise reduction with both prototype test sections P and PCR by comparison with the reference test section E1. From spectral noise levels, this noise reduction can be mainly attributed to the noise reduction at 1000 Hz for P and PCR, and a frequency shift of the maximum noise level towards 630 Hz and 800 Hz. This abatement can be mainly attributed to the low texture levels of the prototype test sections by comparison with the reference road surface, leading to a reduction of tyre vibration. From [13], it has been found that the maximum spectral noise level for road surfaces with relatively high texture levels as E1 is located at 1000 Hz independently of the vehicle speed. On the contrary, for road surfaces with low texture levels as P and PCR, the maximum spectral noise level is speed dependent and is mainly influenced by the tread pattern pitch. Thus, tread pattern impacts play a major role in the noise emission for this kind of road surfaces with low texture levels. The lower noise levels for P by comparison with PCR in the frequency range between 500 Hz and 1000 Hz may be explained by the lower dynamic stiffness measured for P, reducing the magnitude of tyre tread impacts and then noise levels in the medium frequency range [14].

4 Conclusions

In the perspective of an increasing part of EVs in urban area, two VTAC 0/6 mixes have been designed by means of an LCA approach. Two prototype VTAC 0/6 test sections, namely P and PCR, have been implemented on the reference test track of Université Gustave Eiffel in France. Both are based on the same formulation, but one mix (PCR) contains 1.9% of crumb rubber by weight. Quite low MPD and surface texture levels have been measured on both prototype test sections by comparison with a reference DAC 0/10 (namely E1 test section). The measured acoustical absorption was relatively low on both P and PCR test sections, with a maximum absorption coefficient below 0.3 at 2500 Hz. Unexpectedly, the dynamic stiffness on test section P without crumb rubber was lower than on test section PCR containing crumb rubber.

CPX noise has been measured for two tyre models with two different ICEVs. At 50 km/h, the overall CPX noise level reduction for the prototype test sections by comparison with the reference DAC 0/10 was on average 2.6 dB(A) for the Michelin Energy Saver 195/60 R15 tyre and 2.0 dB(A) for the SRTT tyre. CPB noise has been measured for two EV models. At 50 km/h, the overall CPB noise level reduction for the prototype test sections was on average 4.4 dB(A) for the Renault ZOE and 4.2 dB(A) for the Renault KANGOO Z.E. The noise abatement was mainly attributed to the low MPD and texture levels of the prototype test sections, leading to a significant reduction of the maximum noise level at 1000 Hz by comparison with the reference DAC 0/10. On average, test section P without crumb rubber was 0.5 dB(A) quieter than test section PCR, which may be explained by the lower dynamic stiffness measured on test section P.

This study has shown the high potential of noise reduction of both prototype test sections and future work will concern the implementation of such road surfaces in a pilot urban area in Florence (Italy). The results have also emphasized the importance of tyre tread pattern optimization for further noise reduction on this type of road surface with very low MPD and texture levels. This aspect is currently under investigation within the LIFE E-VIA project.

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