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Research Article

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Abstract: Considering the relative quietness of electric motors, tyre/road interaction has become the prominent source of noise emission from Electric Vehicles (EVs). This study deals with the potential influence of the road surface on EV noise emission, especially in urban area. A pass-by noise measurement campaign has been carried out on a reference test track, involving six different road surfaces and five electric passenger car models in different vehicle segments. The immunity of sound recordings to background noise was considered with care. The overall and spectral pass-by noise levels have been analysed as a function of the vehicle speed for each couple of road surface and EV model. It was found that the type of EV has few influence on the noise classification of the road surfaces at 50 km/h. However, the noise level difference between the quietest and the loudest road surface depends on the EV model, with an average close to 6 dBA, showing the potential effect of the road surface on noise reduction in the context of growing EV fleet in urban area. The perspective based on an average passenger EV in a future French or European electric fleet is addressed.

Keywords: electric vehicle, road surface, tyre/road noise, controlled pass-by noise, urban road traffic noise

1 Introduction

According to the European Alternative Fuels Observatory (EAFO) [1], electric vehicle (EV) market is growing fast in

the European area, where about 2.5 million of electric passenger cars were in circulation at the end of 2020. This figure comprises battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs). The market share of new EV registrations over the European area has been reaching 9.4% in 2020 against 3.7% in 2019. Depending on projection scenarios [2], it is expected to reach 15% to 30% of the global vehicle fleet by 2030.

A main advantage of EVs is that there is no exhaust emission while driving in pure electric mode, locally improving air-quality. EVs also contribute to the reduction of CO₂ emission in the struggle against global warming [3]. Another key asset of EVs is the relative quietness of electric motors. This leads to the predominance of tyre/road noise from about 20 km/h at steady speed [4, 5]. According to EEA [6], in 2019 at least 20% of the European population was still exposed to noise levels that are considered harmful to human health. This burden is mainly due to road traffic noise, with more than 100 million EU citizens affected by high noise levels exceeding WHO recommendation [7]. Therefore, the development of low emission zones (as e.g. in [8] or [9]) increasing the share of EVs, together with proper optimisation of road surfaces and tyres of EVs could significantly lessen the exposure of the population to road traffic noise in urban areas. According to [10], based on projection scenarios by 2030, a reduction of L_{den} noise levels of 4 to 7 dBA could be reached in urban area, by a combination of low noise EV tyres and quiet road surfaces.

Existing studies on rolling noise from EV tyres are mainly based on the Controlled Pass-By (CPB) method [11–13] and the Close-ProXimity (CPX) method [14]. In [11], CPB noise levels of four EV models rolling on a dense asphalt concrete (DAC) 0/8 were measured for constant vehicle speed between 15 km/h and 50 km/h. A difference of 6 dBA was found between the quietest and the loudest EV. It was observed that tyre/road noise is more than 10 dBA higher than propulsion noise over the whole speed range. In [12], CPB noise levels of an EV and an internal combustion engine vehicle (ICEV) of equivalent segment and fitted with identical tyres were compared. The speed range was between 10 km/h and 60 km/h and the road surface was a

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DAC. The noise level difference was about 4 dBA at 10 km/h and reduced to only 1.5 dBA at 60 km/h due to the fact that tyre/road noise is dominating at higher speed. Therefore, it was concluded from [11] and [12] that EVs would greatly benefit from low noise tyres and quiet road surfaces for noise reduction in urban area. In [13], CPB noise levels of nine EV tyre models rolling on a DAC 0/11 were compared for vehicle speeds between 30 km/h and 130 km/h. The selection of EV tyre models was essentially based on their low rolling resistance label, which is a parameter affecting the electric vehicle range. The difference between two investigated tyres never exceeded 3.6 dBA at lower speeds (20–50 km/h) and 2.4 dBA between 50 and 120 km/h. It was concluded that rolling noise from EVs did not differ significantly from ICEVs. For these CPB studies, the background noise of the test site was not described in detail. In [14], CPX measurements were performed on 14 different road surfaces. Four different EV tyre models were tested and compared to different ICEV tyre models representative of the market. For some road surfaces, EV tyres were among the quietest tyres at 50 km/h, but such ranking was not systematic. Noise measurements on a test drum facility with the same tyre models showed that the average noise levels of EV tyres and ICEV tyres were similar for most of the tested road surface replicas [15].

In this context, the present work has been carried out within the framework of the European LIFE project E-VIA, which targets the development of low-noise road surfaces and optimal electric vehicle tyres for noise abatement in urban area [16]. One of the first actions of this project was to assess the potential noise reduction considering road surfaces and EVs representative of the current road network and vehicle fleet. Therefore, this paper deals with the influence of the road surface on the noise emission of EVs, especially at urban speed. It relies on CPB noise measurements of recent battery electric passenger cars representative of the current EV fleet. A measurement campaign has been carried out on a reference test track, involving six different test sections and five EV models in different vehicle segments.

The paper is structured as follows. Section 2 concerns materials and method. It describes the test sections and the road surface properties, the tested EVs and tyres, the pass-by measurement procedure and the analysis method. Section 3 gives the main results of the experimental campaign in terms of overall noise levels and spectra for the different combinations of EV and road surface. Section 4 discusses the results by assessing the potential noise emission of the EV fleet for different traffic compositions. Section 5 finally raises the main conclusions of the study.

2 Materials and method

2.1 Test site and road surfaces

The pass-by noise measurement campaign of EVs was carried out in July 2020 on Université Gustave Eiffel reference test track located in Bouguenais (France). This site is composed of 15 different test sections and has been used in the past in many studies related to tyre/road interaction properties, e.g. wet skid resistance, rolling resistance or rolling noise. The test track is not open to traffic and is dedicated to tests with light or medium heavy vehicles only.

Six test sections have been involved in this study, namely A, E1, E3, M2, M3 and N, using the local nomenclature of the test track. Figure 1 gives a close-up picture of the tested road surfaces. A is a Porous Asphalt (PA) 0/6, E1 is a conventionnal Dense Asphalt Concrete (DAC) 0/10, E3 is a Stone Mastic Asphalt (SMA) 0/10, M2 and M3 are two Very Thin Asphalt Concretes (VTAC) of grading 0/6 and 0/4 respectively and N is a DAC 0/8 consistent with ISO 10844 [17]. The latter is the type of road surface required for new tyres and vehicles approval. The five other road surfaces are bituminous asphalt concretes that can be found on the road network, including urban areas.

The main properties of the road surface influencing tyre/road noise have been characterised, i.e. texture for the six test sections and sound absorption for the three porous test sections A, M2 and M3. Only a brief description of these tests is given in the following. For further details on equipment and measurement procedure of texture and sound absorption, the reader can refer to [18].

The texture was measured with a 3D profilometer based on a 2D laser sensor that is moved over the road surface by

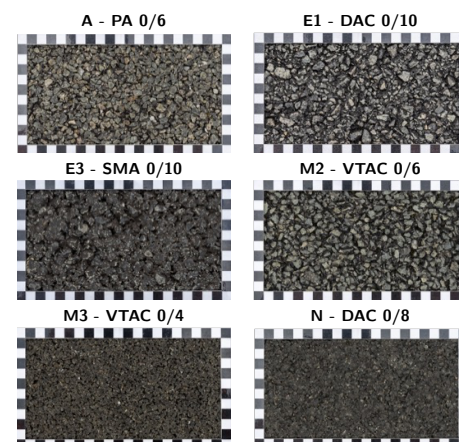


Figure 1: Close-up pictures (20 cm by 10 cm frame) of the 6 road surfaces considered for pass-by noise measurement of EVs

a motorised linear axis in the longitudinal direction and manually via a positioning table in the lateral direction. The final complete texture scans are about 5.8 m long and 0.35 m wide. The longitudinal and transverse sampling intervals are 0.1 mm. The Mean Profile Depth (MPD) and the texture spectra were calculated using longitudinal profiles extracted from the 3D texture scans, according to respectively ISO 13473-1 [19] and ISO 13473-4 [20].

The MPD is given in Figure 2 for the six test sections. The lowest MPD value is obtained for the ISO surface N (0.31 mm) regarding impervious surfaces and for M3 (0.60 mm) concerning sound absorbing road surfaces. Impervious surfaces E1 and E3 have lower MPD values (respectively 0.83 mm and 0.91 mm) than sound absorbing road surfaces A and M2 (respectively 1.13 mm and 1.29 mm).

The texture spectra are given in Figure 3 for the six test sections as a function of the texture wavelength. They represent the energy distribution of the texture signals per one-third octave bands of texture wavelength between 1 mm and 500 mm. A significant range of texture levels is observed, the lowest values being for the ISO road surface N between 1 mm and 200 mm. The wavelength range can be separated into two distinct domains. For wavelengths greater than 12.5 mm, the difference in texture levels is important and can reach up to 13 dB between N and A. The ranking of test sections remains almost unchanged between 200 mm and 12.5 mm. At wavelengths less than 8 mm, the range of texture levels is smaller and decreases from around 10 dB for 8 mm to less than 7 dB for 1 mm. In this range, the ranking of road surfaces is different from that observed at higher wavelengths. The highest levels are observed for A and M2 because of the rather narrow downward peaks and quite large amplitudes which are due to the porosity of the material.

Sound absorption was measured according to the extended surface method of ISO 13472-1 [21] on road surfaces A, M2 and M3 the same week as the pass-by noise measurement campaign. For each road surface, the absorption coefficient was first measured in the middle of the test section at five spots around the position of the pass-by microphone and averaged in the narrow bandwidth frequency domain. Then, the one-third octave band sound absorption coefficient was calculated. As it can be observed in Figure 4, the maximum value of the absorption coefficient α is around 0.6 between 1250 Hz and 1600 Hz for surface A. It is around 0.3 at 630 Hz for M2 and around 0.7 between 800 Hz and 1000 Hz for M3, for which a second significant peak of absorption around 0.5 is observed at 3150 Hz. The other test sections have no significant absorption properties and are considered as impervious road surfaces.

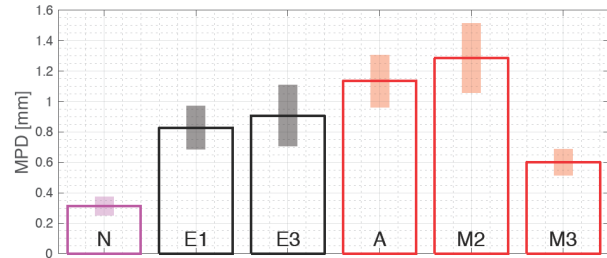


Figure 2: Mean Profile Depth measured on the 6 road surfaces

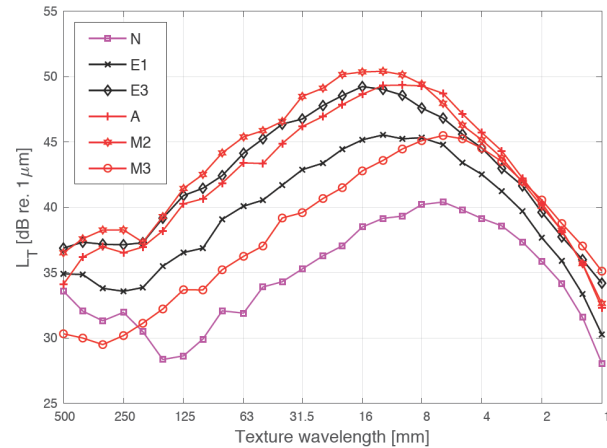


Figure 3: Texture spectra measured on the 6 road surfaces

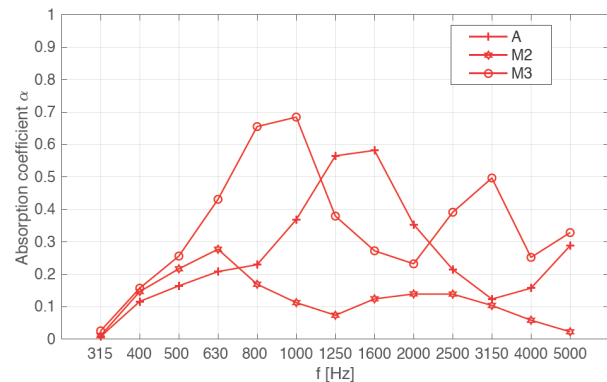


Figure 4: Sound absorption coefficient in one-third octave bands measured on road surfaces A, M2 and M3

2.2 Tested electric vehicles

Based on EAFO data [1], new registrations of electric vehicles by volume in 2019 were dominated by Battery Electric Vehicles (BEV) models. The Tesla Model 3 was by far dominating new registrations in 2019, followed by the Renault ZOE, the Nissan LEAF and the BMW i3. These models of electric passenger cars were also leading the total fleet in the European area. Therefore, they have been involved in the experimental campaign of the present study and complemented by the electric version of the new Peugeot 208.

The chosen EV models cover different segments: *supermini* segment for the Peugeot e-208 and the Renault ZOE, *small family car* segment for the BMW i3 and the Nissan LEAF and *large family car* segment for the Tesla Model 3.

Table 1 gives a brief description of the tested EVs, with ID, make, model, year of construction and mileage at the time of testing.

In more details, the characteristics of the EVs obtained from the Vehicle Identification Number are the following:

- Peugeot e-208 from 2020 of power 100 kW (136 hp), front wheel driven, with battery capacity of 50 kWh and curb weight of 1455 kg;
- Renault ZOE from 2016 of power 65 kW (88 hp), front wheel driven, with battery capacity of 25.6 kWh and curb weight of 1475 kg;
- BMW i3s from 2018 of power 135 kW (184 hp), rear wheel driven, with battery capacity of 33 kWh and curb weight of 1365 kg;
- Nissan LEAF from 2019 of power 110 kW (150 hp), front wheel driven, with battery capacity of 40 kWh and curb weight of 1520 kg;
- Tesla Model 3 Performance Dual Motor from 2019, of power 340 kW (462 hp), all-wheel driven, with battery capacity of 77 kWh and curb weight of 1860 kg.

The tyres fitted on the EVs during the tests are listed in Table 2. Most of the EVs were rented or lent by car dealers. The tyres were in a reasonable state of wear. All vehicles were fitted with four identical tyre models, but the BMW i3 had different tyre dimensions at the front and the rear of the vehicle. It should be noticed that the tyres mounted respectively on the Renault ZOE and the BMW i3 have been specifically designed for these EV models. Although not specific, the tyres on the Peugeot e-208 and Tesla Model 3 Performance are models fitting these EVs at the time of purchase. Considering the low mileage of the Nissan LEAF tested, its tyres are also likely those delivered with the new car. Thus, this tyre panel is a representative sample of those used on the EVs investigated, though other tyres are possible for some of them.

Table 3 gives additional properties of the tested tyres, i.e. the Height to Width Ratio (HWR), defined as the diameter of the unloaded tyre over the tyre width, the Shore A hardness and the inflation pressure of the tyres. The two latter have been measured on cold tyres prior to the pass-by noise testing. It should be noticed that BMW i3 tyres have higher HWR than other tyres, which is due to their tall and narrow shape. The tyre Shore A hardness ranges between 56.1 and 67.9, respectively for the Peugeot e-208 and the Tesla Model 3. The inflation pressure was fixed following the specification of each vehicle.

Table 1: Description of the five tested EV models

ID	Make	Model	Year	Mileage
e208	Peugeot	e-208	2020	3278 km
zoe	Renault	ZOE	2016	5840 km
i3	BMW	i3s	2018	12328 km
leaf	Nissan	LEAF	2019	5637 km
model3	Tesla	Model 3	2019	31498 km

Table 2: Description of the tyres fitted on the tested EVs. Dimensions are followed by the load index and the speed rating

ID	Tyre model	Dimensions
e208	Michelin Primacy 4	195/55 R16 87H
zoe	Michelin Energy E-V	185/65 R15 88Q
i3 (front)	Bridgestone Ecopia EP500	175/55 R20 89T
i3 (rear)	Bridgestone Ecopia EP500	195/50 R20 93T
leaf	Michelin Energy Saver	205/55 R16 91V
model3	Michelin Pilot Sport 4 S	235/35 ZR20 92Y

Table 3: Additional properties of the tested EV tyres

ID	HWR	Hardness (Shore A)	Pressure (bars)
e208	3.2	56.1	2.5
zoe	3.4	61.4	2.5
i3 (front)	4.0	64.2	2.3
i3 (rear)	3.6	65.2	2.8
leaf	3.1	62.2	2.5
model3	2.9	67.9	2.9

2.3 Pass-by measurement

2.3.1 Experimental set-up

Controlled Pass-By (CPB) noise measurements were performed with a microphone located at the roadside, on the left of the vehicle, at the standard ISO 11819-1 [22] position, i.e. 7.5 m from the middle of the lane centre and 1.20 m above the road surface. On each test section, several runs were performed at constant speed from 20 km/h to 110 km/h with a 5 km/h step. At low speed, the Acoustic Alerting Vehicle System (AVAS) was switched off during the tests when this equipment was available, except for the Peugeot e-208 for which the deactivation was not possible and the speed without AVAS ranged from 30 km/h to 110 km/h.

Figure 5 illustrates the pass-by noise measurement with the Nissan LEAF rolling on the test section E1. Two infrared cells respectively located at 5 meters before and after the microphone position, together with two reflective plates fixed on the vehicle (resp. near the front and the rear of the vehicle body) provide accurate information on the vehicle position and speed at pass-by.



Figure 5: Experimental set-up for CPB noise tests, here exemplified in the case of the Nissan LEAF rolling on test section E1

2.3.2 Maximum pass-by noise levels

For each run, the acoustic pressure signal $p_A(t)$ was recorded by means of a digital audio recorder and later processed according to ISO 11819-1 [22]. The A-weighted noise level L_{AF} , based on fast time integration, was calculated as follows:

$$L_{AF}(t) = 10 \log_{10} \left(\frac{1}{\tau_F} \int_{-\infty}^t \frac{p_A^2(\xi) e^{-(t-\xi)/\tau_F}}{p_0^2} d\xi \right) \quad (1)$$

with constant time $\tau_F = 0.125$ s and reference acoustic pressure $p_0 = 2 \cdot 10^{-5}$ Pa. Then, the maximum overall A-weighted sound pressure level $L_{Amax,m}$ was identified as the maximum value of the time signature $L_{AF}(t)$. One-third octave band instantaneous sound pressure levels $L_{Amax,m}(f)$ were also identified at the instant when the maximum noise level $L_{Amax,m}$ occurred, for one-third octave frequency bands from 100 Hz to 5 kHz. Figure 6 gives the time signature $L_{AF}(t)$ of the Nissan LEAF when passing-by at 50 km/h. The signals of the infrared cells, plotted in red, are used for the calculation of the vehicle speed, as mentioned above.

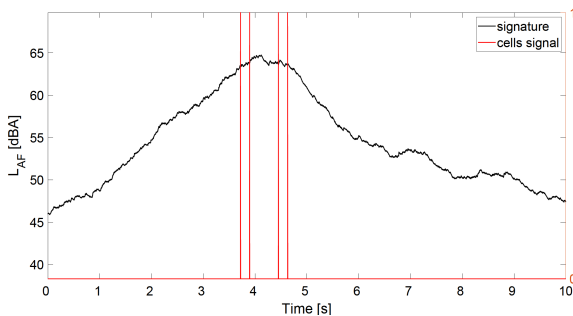


Figure 6: Time signature (black line) of the vehicle pass-by noise level $L_{AF}(t)$ in the case of the Nissan LEAF rolling on test section E1 at 50 km/h. Red lines are infrared cells signals

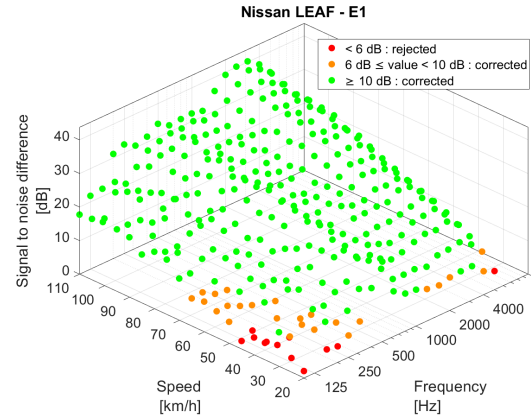


Figure 7: Signal to background noise difference as a function of speed and third octave frequency bands for the Nissan LEAF rolling on E1 test track

For each combination of EV and road surface, the background noise level L_{bn} was recorded at the pass-by microphone. The difference between the measured maximum noise level and the background noise level, ΔL , is defined by:

$$\Delta L = L_{Amax,m} - L_{bn} \quad (2)$$

If $\Delta L < 6$ dBA, the measurement was disregarded. If $\Delta L \geq 6$ dBA, a correction was applied to the overall and the one-third octave frequency band measured noise levels. This correction expresses as follows:

$$L_{Amax} = L_{Amax,m} - \Delta L_{Amax} \quad (3)$$

with:

$$\Delta L_{Amax} = -10 \log_{10} \left(1 - 10^{-\frac{\Delta L}{10}} \right) \quad (4)$$

In practice, for the overall noise levels, the signal to background noise difference ΔL was above 10 dBA for most of the configurations and the correction term was minor. In the frequency domain, the correction depended on the configuration and on the background noise level at the time of the test. The influence of the background noise level was essentially critical at low vehicle speed and in the low frequency range, below 315 Hz. Figure 7 gives the values of ΔL as a function of the frequency and the vehicle speed in the case of the Nissan LEAF rolling on test section E1. It is clear that the occurrence of invalid data (i.e. $\Delta L < 6$ dBA) is limited to very low frequency and speed.

2.3.3 Noise levels versus vehicle speed regressions

The corrected CPB overall noise levels L_{Amax} increase linearly with the logarithm of speed (Figure 8), which is a common behaviour when rolling noise is the dominant noise

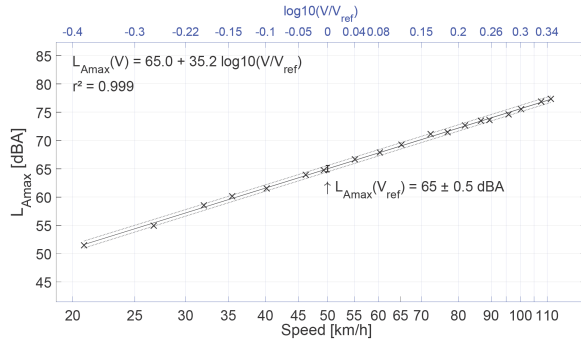


Figure 8: Example of logarithmic regression (solid line) of the overall maximum noise level L_{Amax} versus vehicle speed V in the case of the Nissan LEAF rolling on the E1 test section. Crosses are the experimental data. $V_{ref} = 50$ km/h

source. They were analysed through a logarithmic regression versus vehicle speed V :

$$L_{Amax}(V) = L_{Amax}(V_{ref}) + b_{L_{Amax}} \log_{10}(V/V_{ref}) \quad (5)$$

where V_{ref} is a reference speed, $L_{Amax}(V_{ref})$ is the overall regression noise level (in dBA) at the reference speed, and $b_{L_{Amax}}$ is the slope of the regression in dBA per decade of speed. The same speed dependency was assumed for 1/3 octave band noise levels (in dBA) at frequency f :

$$L_{Amax}(V, f) = L_{Amax}(V_{ref}, f) + b_{L_{Amax}}(f) \log_{10}(V/V_{ref}) \quad (6)$$

where $L_{Amax}(V_{ref}, f)$ is the spectral regression noise level (in dBA) at the reference speed, and $b_{L_{Amax}}(f)$ is the slope of the regression in dBA per decade of speed in the one-third octave band of central frequency f . In this study the reference speed is fixed to $V_{ref} = 50$ km/h.

Noise data can be analysed by means of a logarithmic regression on the experimental data for each combination of EV and road surface. Figure 8 plots the regression line obtained from the overall noise level L_{Amax} and the vehicle speed V in the case of the Nissan LEAF rolling on the E1 test section. The values of the parameters $L_{Amax}(V_{ref})$ and $b_{L_{Amax}}$ are displayed on the graph. The standard deviation of the parameters can be estimated via the 95% confidence interval of the regression. The coefficient of determination of the regression r^2 is also indicated and is very close to 1 in most of the configurations.

3 Results

3.1 Regression coefficients

Table 4 gives the overall noise levels $L_{Amax}(50)$ and the regression slopes $b_{L_{Amax}}$ for the 30 combinations of EV and

Table 4: CPB regression slopes $b_{L_{Amax}}$ (in dBA/dec) and overall noise levels $L_{Amax}(50)$ (in dBA, not corrected in temperature) at 50 km/h for the 6 test sections and the 5 tested EVs

Surface	T_{air} (°C)	$b_{L_{Amax}}$	$L_{Amax}(50)$
Peugeot e-208			
A	21.1	30.2 ± 1.1	61.6 ± 0.8
E1	27.6	34.6 ± 1.3	64.2 ± 1.0
E3	27.6	34.9 ± 1.0	65.0 ± 0.7
M2	23.3	29.6 ± 1.5	62.3 ± 1.1
M3	23.3	32.4 ± 1.6	58.7 ± 1.1
N	23.0	32.6 ± 1.5	61.6 ± 1.1
Renault ZOE			
A	23.7	28.9 ± 1.8	63.6 ± 1.7
E1	28.7	33.2 ± 1.4	66.0 ± 1.3
E3	28.7	34.8 ± 1.4	66.6 ± 1.4
M2	23.6	32.1 ± 1.1	63.9 ± 1.0
M3	26.8	28.9 ± 1.2	61.5 ± 1.1
N	33.4	32.7 ± 1.6	64.2 ± 1.4
BMW i3			
A	28.6	34.1 ± 1.6	61.4 ± 0.9
E1	26.4	34.7 ± 1.1	64.0 ± 1.1
E3	26.4	34.9 ± 1.0	65.0 ± 1.0
M2	31.4	33.9 ± 1.0	61.5 ± 1.0
M3	32.1	28.1 ± 1.8	59.3 ± 1.1
N	28.1	34.1 ± 1.4	62.0 ± 0.8
Nissan LEAF			
A	28.1	31.5 ± 1.2	62.9 ± 1.0
E1	27.6	35.2 ± 0.6	65.0 ± 0.5
E3	27.6	36.4 ± 0.9	66.0 ± 0.8
M2	32.4	32.1 ± 0.9	62.7 ± 0.8
M3	32.1	28.6 ± 1.4	61.3 ± 1.3
N	28.1	37.0 ± 2.2	64.3 ± 2.0
Tesla Model 3			
A	29.4	29.5 ± 1.6	63.1 ± 1.3
E1	26.6	32.8 ± 0.6	66.2 ± 0.6
E3	26.6	34.8 ± 0.9	67.0 ± 0.9
M2	26.6	30.3 ± 1.4	64.0 ± 1.3
M3	31.4	31.0 ± 1.7	60.1 ± 1.6
N	31.4	33.1 ± 1.0	63.0 ± 1.0

test section. The indicated uncertainties correspond to the standard deviation of the regression parameters. The average air temperature T_{air} during the test is also given, but the noise levels in the table are not corrected in temperature. From these data, one can estimate the CPB noise level at any vehicle speed between 20 and 110 km/h. In the following, the analysis focuses on the results at the reference urban speed of 50 km/h.

3.2 Classification of overall noise levels

For the sake of analysis, the overall noise levels at 50 km/h are plotted in two different ways in Figures 9 and 10. The noise levels are corrected in temperature according to [23]

for proper comparison of the different configurations. The reference air temperature is $T_{air} = 20^\circ\text{C}$.

The acoustical classification of the six test sections is given in Figure 9 for each tested EV. For all EVs, the quietest road surfaces in increasing order are M3 and A and the loudest ones in increasing order are E1 and E3. In between, the ranking of road surfaces M2 and N varies from one EV to another. It is observed that road surfaces with low texture levels (i.e. M3 and N) and/or absorption properties (A, M2 and M3) are among the quietest test sections. This is due to the reduction of tyre/road noise which is the dominant source for EVs during CPB tests at constant speed. The difference between the quietest and the loudest test sections (resp. M3 and E3) is quite influenced by the EV model and varies from 4.7 dBA for the Nissan LEAF to 6.9 dBA for the Peugeot e-208 and the Tesla Model 3. Considering the 30 road/vehicule configurations, a difference of 8.8 dBA was observed between the quietest and the loudest combinations (i.e. e208/M3 vs. model3/E3).

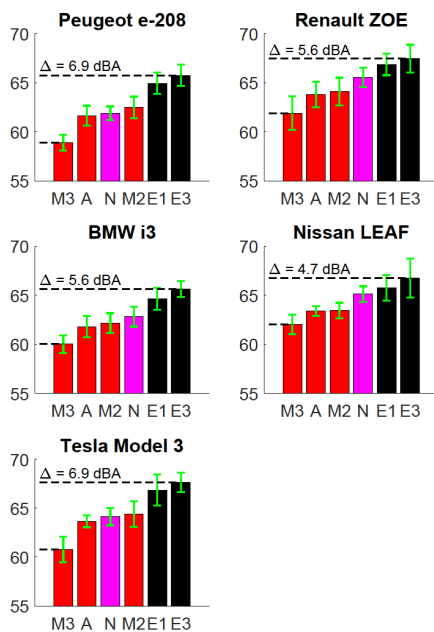


Figure 9: Overall noise levels classification of the 6 test sections for each EV at $V_{ref} = 50$ km/h (in dBA, corrected in temperature at $T_{air} = 20^\circ\text{C}$)

Figure 10 gives the acoustical classification of the 5 tested EVs for each road surface. The Peugeot e-208 and the BMW i3 are the quietest vehicles, while in most cases the Renault ZOE is the loudest vehicle, or nearly. The ranking shows that there is no clear relationship between the EV segment and its overall noise level. The difference between the quietest and the loudest EV ranges from 2 dBA for

test section E3 to 3.6 dBA for test section N. It is likely that tyre/road noise emission on M3 and N, with low MPD and texture levels, is more sensitive to the tyre tread pattern, which could explain the higher difference in noise levels on these test sections.

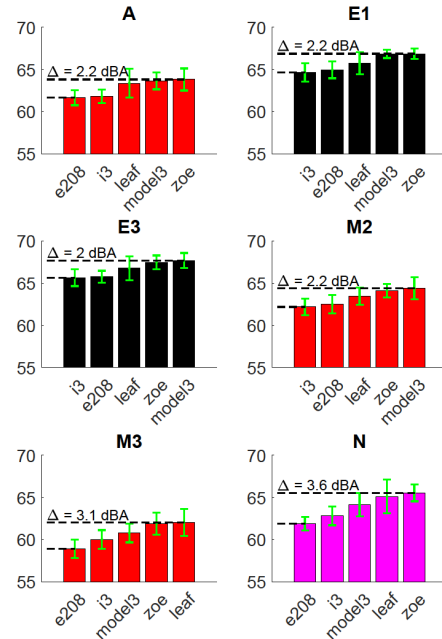


Figure 10: Overall noise levels classification of the 5 EVs for each test section at $V_{ref} = 50$ km/h (in dBA, corrected in temperature at $T_{air} = 20^\circ\text{C}$)

3.3 Spectral noise levels

Figure 11 gives the CPB regressed noise spectra at 50 km/h for each vehicle, considering the 6 test sections. Independently of the test section, a peak is observed at low frequency for some vehicles, i.e. at 250 Hz for the Peugeot e-208 and the Nissan LEAF, and at 315 Hz for the Renault ZOE. The dispersion among road surfaces depends on the EV model, with variations up to 15 dBA for the Tesla Model 3 above 630 Hz.

For the impervious road surfaces (i.e. E1, E3 and N), a maximum is observed at 1000 Hz for all EVs but the Tesla Model 3 on E3, for which the maximum is slightly shifted at 800 Hz. This peak at 1000 Hz is typical of the tyre/road noise emission on this kind of dense surfaces. It may have several origins according to [24]. For these road surfaces, it is clear that the noise levels at frequencies below 1000 Hz are smaller for the test section N due to its low texture levels over the large texture wavelength range (Figure 3), reduc-

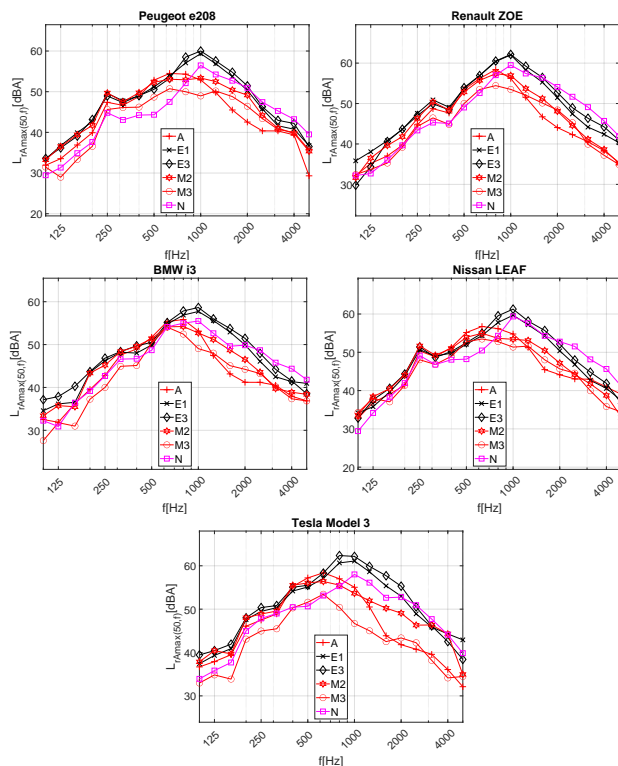


Figure 11: Spectra at the reference speed of 50 km/h

ing tyre vibration [25]. Between 1000 Hz and 2000 Hz, the difference between N and E1 or E3 depends on the configurations. At higher frequency above 2000 Hz, test section N is louder than E1 and E3. This can be explained by lower texture levels at small texture wavelengths for N (Figure 3), increasing air-pumping mechanisms [25].

In the case of the porous test sections (i.e. A, M2 and M3), the peak is less pronounced than for dense surfaces and is shifted at a lower frequency between 630 Hz and 800 Hz, depending on the configuration. Noise level reduction at frequencies above this maximum are clearly due to the sound absorption properties of these road surfaces (Figure 4). It can be noticed that for test sections A and M2, noise levels at frequencies below the peak position are in the same order of magnitude than noise levels of test sections E1 and E3. This is again due to high texture levels for A and M2 in the large texture wavelength range. On the contrary, test section M3 is quieter than A and M2 at low frequency due to lower texture levels at large texture wavelength, favourable to the reduction of tyre vibration. Combined with sound absorption properties, this makes test section M3 the quietest road surface for all tested EVs.

4 Discussion: average EV in urban driving conditions

More and more European cities already have or are introducing zones with an access limited to low emission road vehicles, firstly motivated by air quality. Time restrictions may be seasonal, limited to certain days of the week or day slots, or permanent [26]. In these areas, electrically powered vehicles are allowed without restriction. There is a trend towards stricter access conditions by banning an increasingly wide range of ICE vehicle categories and favouring electromobility. For instance, except for a few exempted vehicles, the city of Florence (Italy) already promotes the use of electric vehicles within centre areas. Similarly, the city of Madrid (Spain) allows free access to inner city to EVs (battery or fuel cell) and those hybrid vehicles with a minimum 40 km electric range [9]. Other cities are planning similar policies in the more or less near future, like Paris (France) in its Phase 6 drafted to 2030 [8]. Urban road traffic situations involving only electric vehicles are likely to multiply.

Since noise level and spectrum radiated at electric vehicle pass-by depend both on vehicle type and road surface, the breakdown of the EV segments within the traffic may impact traffic noise. Statistics provided by EAFO, informing on the 10 best-selling electric passenger-car models in 2020 by country or in all Europe, point out spatial dissimilarities in the most popular segments. For example, while France and Italy prefer small EVs, these are uncommon in Norway. The distribution in Germany is similar to the average across Europe (Table 5). The 10 best-selling EV models are 83.3% of all passenger EVs sold in France, but 69.2% in whole Europe where the number of models available is larger at this wider geographical scale.

As shown in Figure 10, the noise level is not specifically related to the EV segment, but depends on the vehicle model, including its tyre characteristics. At low speed and

Table 5: Breakdown of the 10 best-selling EV models in 2020 per vehicle class, based on EAFO statistics [1] and Euro NCAP vehicle classes [27]

	supermini	small family car + small off-road car	large family car + large off-road car
France	67.4%	21.6%	11.0%
Italy	73.7%	12.2%	14.1%
Germany	42.9%	38.1%	19.0%
Norway	5.6%	64.1%	30.2%
Europe	41.7%	37.7%	20.6%

in some frequency ranges, the drive train may also contribute. To address traffic noise, involved in noise mapping, the noise emission of an average EV is considered in this section, in connection with the various road surfaces, in terms of frequency distribution and global noise levels.

As a first estimation towards EV traffic noise emission, the average EV is defined according to the fleet distribution of the 10 best-selling ones in 2020, in France on the one hand and in Europe on the other hand. Among those, the EV models tested in this study form 62.9% in France (resp. 39.1% in Europe). It is assumed that the EV models tested are acceptably representative of the passenger EV fleet, but with a higher reliability in France. Considering the strong percentage of Renault ZOE in the *supermini* class, the average *supermini* noise level (resp. spectrum) is weighted as 2/3 of Renault ZOE contribution and 1/3 of Peugeot e-208. In the *small family/off-road car* class, the same weight is assigned to BMW i3 and Nissan LEAF. Finally, the *large family/off-road car* class is represented by the Tesla Model 3. These three classes are then weighted according to their breakdown in the geographical region considered, as listed in Table 5, to provide the global noise level (resp. spectrum) of the average passenger EV on each road surface. Beyond EV models, it is known that the tyre features impact rolling noise emission. As a reminder of section 2.2, it can be reasonably assumed that the EVs tested, involving either specific or originally fitted tyres on vehicle purchase, provide a decent insight into the current EV fleet.

In order the spectrum of an average EV to be assessed from vehicle contributions taken in similar situations, the individual vehicle spectra shall be taken at the same temperature. Whereas consistent temperature correction coefficients are available in the literature for global levels, there is no agreement on correction per frequency under conditions analogous to the present study (i.e. real pass-by conditions, similar road surface). Therefore, the temperature corrections used on global levels in section 3.2 are applied uniformly over the entire frequency range to provide vehicle noise spectra at the reference air temperature of 20°C and derive the average EV spectrum. Vehicle noise emission models provided for noise mapping, like in the European method CNOSSOS-EU [28], mostly rely on frequency spectrum data and global noise levels are computed by frequency integration. The same approach has been taken here to derive the global pass-by noise of an average EV (Figure 12).

It turns out that considering the French EV traffic mix or the European one does not really matter, since the distribution of noise levels is poorly correlated with the vehicle segment. Therefore, the distribution of EV classes in the traffic has a very minor impact on average noise spectrum

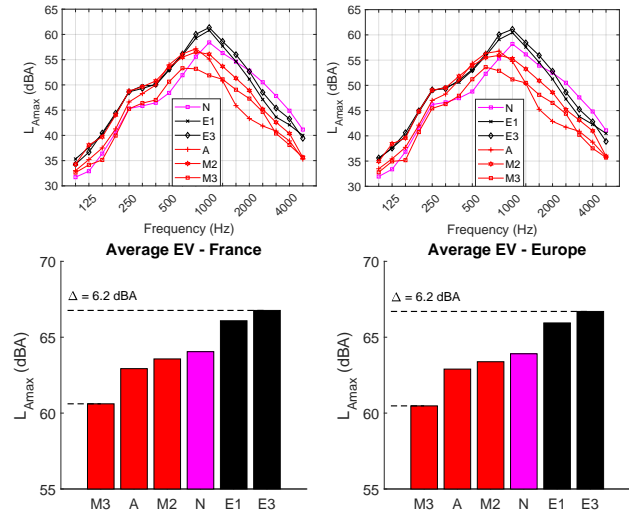


Figure 12: Noise spectrum (top) and road surface ranking according to global noise (bottom) for the French (left) and the European (right) average EV at $V_{ref} = 50$ km/h and $T_{air} = 20^\circ\text{C}$

and average global noise, whatever the road surface in urban situation. However, the influence of the road surface type is predominant and is the real lever for mitigating the noise from an EV traffic, equally irrespective of the EV traffic mix, with a possible overall stake of 6.2 dB(A) at road-side over the panel of pavements tested. This range may be a low estimate for the European region, considering that road surfaces with a maximum aggregate size of 11 mm or 16 mm used as references in some countries [29] are likely to lead to higher noise levels than the SMA 0/10 used in this study. In frequency, with reference to dense surfaces, the maximum spectrum contribution is reduced and shifted towards lower frequencies with absorbing surfaces: from third octave 1000 Hz on dense surfaces to 800 Hz or even 630 Hz for the quietest road surface (M3).

5 Conclusions

In this study, the CPB noise levels of five EV models have been measured on six reference road surfaces with different texture and sound absorption properties. CPB tests have been performed at constant vehicle speed ranging between 20 km/h and 110 km/h. Special care was taken towards the immunity of the pass-by maximum noise levels and associated spectra towards the background noise levels. Invalid data (i.e. with $\Delta L < 6$ dBA) have been pointed out in the frequency domain, at low vehicle speed only and mainly in the frequency range below 315 Hz. For overall and spectral noise levels with $\Delta L \geq 6$ dBA, a correction factor was applied.

A logarithmic regression of noise levels versus vehicle speed was performed from the set of valid data. This gives the possibility to assess the CPB noise levels at any vehicle speed for the 30 combinations of EV and test section. The results have been further analysed at the reference urban speed of 50 km/h.

Considering overall noise levels, a maximum difference of 8.8 dBA was found between the quietest and the loudest combinations. Independently from the tested vehicle, the quietest test section was always M3 (VTAC 0/4) and the loudest test section E3 (SMA 0/10). The noise reduction between E3 and M3 could vary from 4.7 dBA (Nissan LEAF) to 6.9 dBA (Peugeot e-208 or Tesla Model 3). For a given test section, the noise levels among EVs varied in a range between 2 dBA on test section E3 and 3.6 dBA on test section M3. The analysis of spectral noise levels has shown that noise absorption properties and low texture are the main levers for efficient noise abatement from the road surface.

In the discussion, the noise spectrum of an average EV was calculated from the current EV traffic mixes in France and Europe. Whereas the EV traffic composition actually plays an insignificant role, the influence of the road surface was found to be predominant for noise reduction, with a possible overall stake of 6.2 dBA at roadside over the tested panel of pavements with a maximum aggregate size of 10 mm. In frequency, with reference to dense surfaces, the maximum spectrum contribution was reduced and shifted towards lower frequencies with absorbing surfaces. Thus, it can be concluded that the main noise reduction is obtained when acting on the road surface. A proper optimisation of EV tyre properties can further enhance this noise abatement, by providing an additional, albeit more limited, range of action [30].

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