Investigation of electric vehicle noise sources on low-noise road surfaces

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ABSTRACT

Electric vehicles (EVs) constitute an increasing share of the vehicle fleet, in particular regarding light vehicles. This ratio may be significantly enhanced in urban areas that favour access to low-emission vehicles. Acknowledged to be quieter than conventional vehicles due to a lower propulsion noise, EVs feature a comparatively heightened tyre-road noise contribution, further reduction of which can be achieved by selecting appropriate low-noise road surfaces. These factors may result in modified noise source distributions on the vehicles. In the framework of the LIFE E-VIA project, noise source contributions have been investigated on several light EVs from different segments on a reference ISO road surface, by using a microphone array with dedicated processing. Wide ranges of speeds and driving conditions were considered. In a second step, particular focus has been placed on the road surfaces, comparing the noise sources of selected EVs either driving on the ISO road surface or on low-noise prototypes optimized for EVs and developed within the project. These are two similar versions of a very thin asphalt concrete 0/6, one containing crumb rubber. The presentation gives an overview of the EV noise source behaviour and their ranking with regard to the various situations tested in the project.

1. INTRODUCTION

In the current context of great concern about climate change and the harmful impact of fossil fuels, both battery and plug-in hybrid electric vehicles represent a strongly increasing share of the light vehicle fleet on the road network, especially in urban areas but even beyond [1]. With low propulsion noise compared to conventional vehicles, they also offer a solution for reducing road traffic noise at urban speeds, the rolling noise from tyre/road contact thus becoming the main noise source from low speeds. Controlling this noise component, even at urban speeds, through the design of both optimised road surfaces and tyres for electric vehicles (EVs) is a key issue considered within the framework of the LIFE E-VIA project [2].

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A first phase of the project investigated the noise emission of a sample of common light electric vehicles driving on a selection of road surfaces available on the reference test track of Université Gustave Eiffel in Nantes (France), with regard to several physical and acoustical road surface properties. Standard Controlled Pass-by (CPB) measurements were used to derive the ranking of EVs vs. road surface [3]. Two versions of a low-noise road surface, optimised from an acoustical and life cycle perspective [4], one distinctive by the addition of crumb rubber, have then been developed and thoroughly assessed [5], before further experimental implementation under real traffic conditions in Florence (Italy).

The previous CPB analysis, relying on a microphone at roadside standard position 7.5 m from lane centre, has been deepened by simultaneous noise source investigation focusing on their location and prominence over the vehicles and on their behaviour according to driving conditions on a reference road surface and the two road surface prototype versions. The main features of this noise source analysis are the subject of this paper. First, the experimental approach, involving a microphone array, is presented (§ 2). Then, the noise source distribution is considered for the sample of six EVs driving on a reference road surface DAC 0/8 consistent with ISO 10844 (§ 3). Finally, a selection of three EVs is used for assessing the changes on their noise sources introduced by the project prototype surfaces (§ 4). For further details, including frequency behaviour, a more comprehensive analysis of the EV noise source behaviour is available in the LIFE E-VIA project deliverable B2 [6].

2. EXPERIMENTAL APPROACH

2.1. Test site and road surfaces

The acoustical characterisation of a set of electric vehicles was carried out on Université Gustave Eiffel reference test track, located in Bouguenais (France), that offers a range of road surfaces. This test site was also chosen for hosting the prototype of low-noise road surface designed within the LIFE E-VIA project, to be thoroughly assessed before full-scale implementation in the pilot site of Florence in Italy.

Noise source characterisation of various EVs at pass-by has been performed on a DAC 0/8 road surface (here named N), with a very low mean profile depth (MPD), such as the one prescribed for new tyres and vehicles approval (ISO 10844 [7]).

The low-noise prototype road surface developed within LIFE E-VIA project is a VTAC 0/6, available in two versions, one containing 1.9% of crumb rubber (here named prototype PCR), while the other has no crumb rubber (prototype P). Each prototype test section is 4 m wide and 57 m long and the road surface layer has a thickness of 25 mm. Whereas road surface N has no sound absorption properties, prototypes proved to offer a slight absorption in the range 2000-3150 Hz with a maximum value of 0.27 at 2500 Hz for road surface P (resp. 0.17 for road surface PCR) [5].

Close-up views of the road surfaces are given in Figure 1. All exhibit a fine grading and flattening of aggregates.

Figure 1: Close-up pictures of the road surfaces (frame size: 20 cm by 10 cm).

2.2. Electric vehicles

The EV models tested were in accordance with new European registrations of electric passenger cars in the period 2019-2020, with Tesla Model 3 by far dominating, followed by Renault ZOE, Nissan LEAF and BMW i3. The newcomer electric version of Peugeot 208 was also tested. The chosen EV models cover different car classes: *supermini* for the Peugeot e-208 and the Renault ZOE, *small family car* for the BMW i3 and the Nissan LEAF and *large family car* for the Tesla Model 3. Additionally, one Renault Kangoo ZE, a top-seller in the light commercial vehicle category, was also included in the study. The six EV models, shown in Figure 2, were tested on road N for noise source comparison.

All vehicles are front-wheel driven, except the BMW i3 which is rear-wheel driven and the Tesla Model 3 all-wheel driven. They were fitted with their actual commercial tyres, all in a reasonable state of wear. All vehicles were fitted with four identical tyre models, except the BMW i3 having different tyre dimensions at the front and at 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 by manufacturers for these EV models.

For the tests on the prototype road surfaces P and PCR, the Renault ZOE, a Nissan LEAF and the Renault Kangoo ZE were selected for investigation. In this case, the Nissan LEAF was actually from a different generation than the one tested on road N and had other tyre models. Thus, to distinguish them, they are numbered respectively #1 and #2 for the tests on N and on P/PCR.

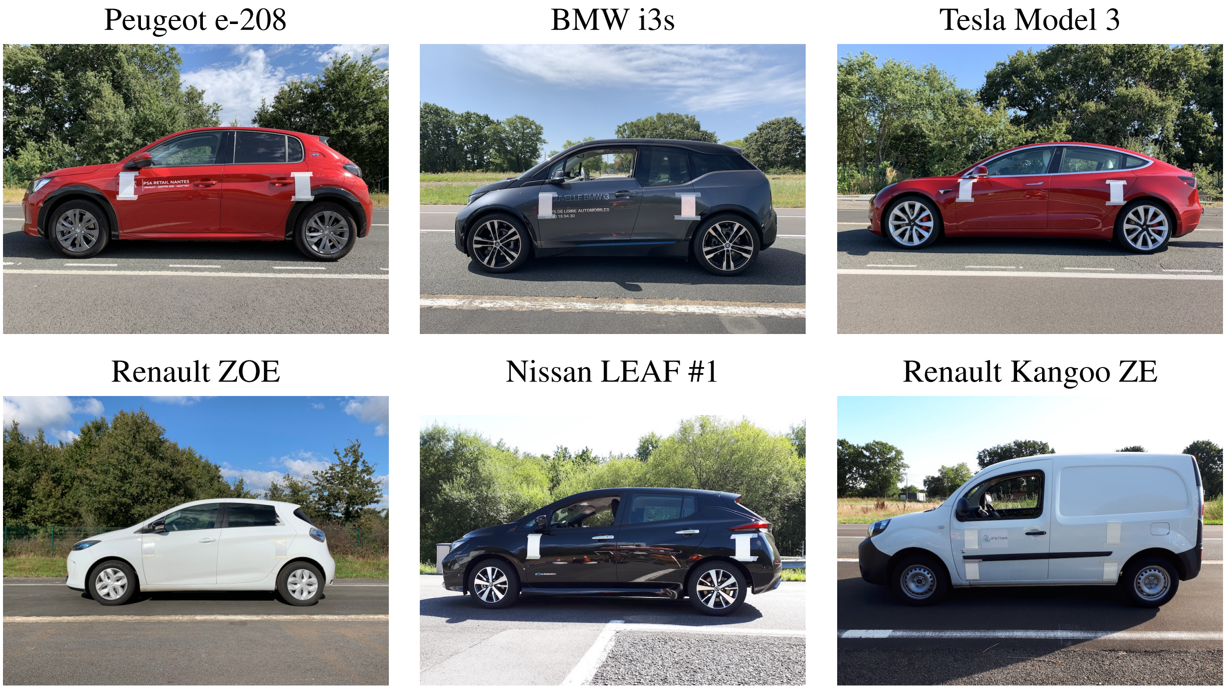

Figure 2: Views of the 6 EV models tested

2.3. Pass-by acoustical tests

Pass-by tests were carried out in different driving conditions: at constant speed, in acceleration and in deceleration (regenerative braking). On each test section, several runs were performed at constant speed in the range between 20 km/h and 110 km/h, with a 5 km/h step. At low speed, the Acoustic Vehicle Alerting System (AVAS) was switched off during the tests when this equipment was available, except for the Peugeot e-208 where deactivation was not possible and the speed without AVAS ranged from 30 km/h to 110 km/h.

Acceleration tests were performed at full acceleration conditions. The test vehicles accelerated over a minimum length of 10 m centred on the microphone, from various initial speeds selected in 10 km/h steps. The actual range of initial speeds depended on the power of the tested vehicle. Among the driving modes available on each vehicle, the option giving high acceleration rates was selected in order to test the toughest conditions.

Pass-by noise tests in decelerating conditions were performed with regenerative braking only. In this mode, the vehicle decelerates when releasing the gas pedal, without pressing the brake pedal. The test vehicle decelerated from the entrance of the test section over a minimum length of 10 m centred on the microphone, with several initial speeds selected between 40 and 90 km/h. On each vehicle, the driving mode providing the most efficient energy recovery, then the highest deceleration rate, was selected.

2.4. Array and processing

The microphone array, associated with specific array processing, performs acoustic imaging of the vehicle at pass-by and offers the possibility to geometrically separate and identify noise source contributions to the vehicle noise emission. The microphone array is composed of 61 microphones arranged in a plane on several concentric circles, the outer circle having a diameter of 2.56 m (Figure 3). The array is placed at roadside, about 3.5 m from the track centre. For the implementation of the array processing, kinematic information on the vehicle motion is required. This is provided by infrared cells informing on vehicle position and speed, and completed by a rangefinder giving the distance between the actual vehicle path and the array plane.

The array processing involves classical beamforming for spherical incident waves with dedopplerisation. The dedopplerised microphone signals are filtered in third-octave bands for next noise source investigation and imaging. Constant array aperture is designed over the frequency range 500-5000 Hz. At frequencies lower than 500 Hz, the target aperture value cannot be satisfied and the array resolution reduces with the decreasing aperture. The focal point is steered with any targeted sound source on the moving vehicle, over a range [-20°, +20°] centred on the direction normal to the array centre, whatever the vehicle speed. The noise level delivered by the processing is the A-weighted equivalent noise level of the beamforming output signal, calculated on the time duration T_{scan} corresponding to the source motion within the steering range [-20°, +20°]. For a common comparison basis among driving conditions and vehicles, the reported levels are scaled to the reference distance of 2.7 m. More detailed information on the implemented array processing is available in the project deliverable [6].

Figure 3: Microphone array and vehicle pass-by on road surface N

For each vehicle pass-by, a noise source map of the vehicle is produced in dB(A), in each one-third octave band from 100 Hz to 5000 Hz and then in overall levels over the same frequency range. The noise levels received from any location on the vehicle side are displayed according to a colour scale, with a 0.5 dB(A) step for easy reading.

In most cases, the noise sources detected lie mainly in the close neighbourhood of the wheels. They include the rolling noise but, if so, may also contain propulsion noise when the motor is located close to the axle. For quantifying in a simple way the noise emission from each wheel zone, the maximum value of the above equivalent beamformed level from the array has been taken over the area closely surrounding the wheel and the tyre/road contact. This allows noise contribution from each wheel zone to be plotted as a function of speed and to be compared between vehicles and road surfaces.

3. NOISE SOURCE COMPARISON OF SEVERAL EVS ON ROAD SURFACE N

3.1. Constant speed

An illustration of the noise source maps of the six EVs is given at a constant speed of 50 km/h in Figure 4, in overall levels taken over the frequency range [100 - 5000 Hz]. For an overview at all speeds, the contribution of each wheel zone as a function of speed is displayed in Figure 5, also in overall levels over the same frequency range. In a general way, it is worth highlighting that the rear wheel zone is often the one contributing most to noise emission and that the ranking of wheel zones is not necessarily steered by the driving axle and the nearby presence of the motor. In frequency accordingly (not illustrated here), the involvement of components with frequency band and level varying with speed is observed on both wheels in many cases, suggesting the major contribution of rolling noise, possibly enhanced on the rear wheel by the horn effect and bodywork shape.

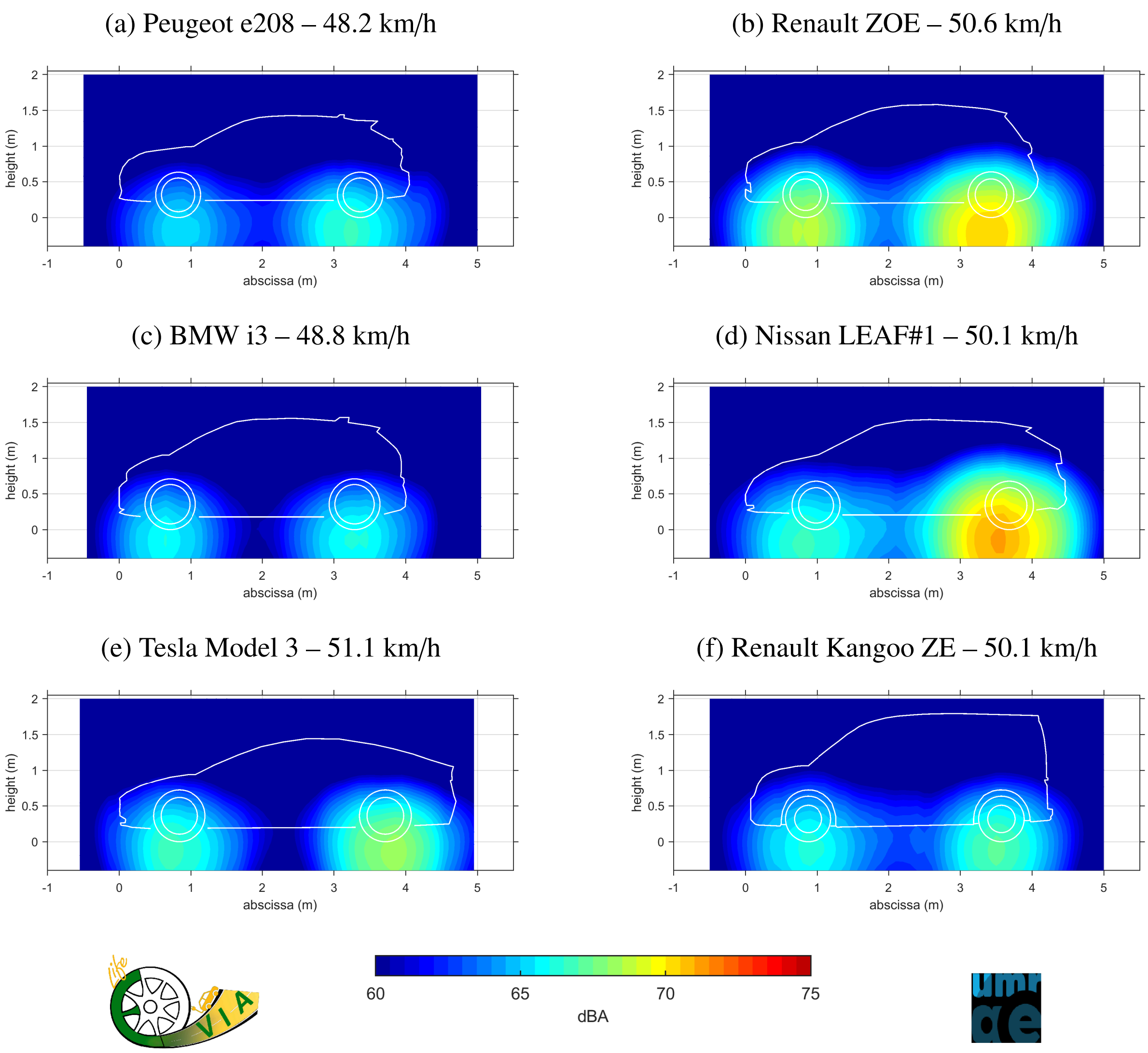

Figure 4: Noise source maps of the EVs at a constant speed close to 50 km/h on road surface N – A-weighted overall noise levels at the reference distance of 2.7 m – Colour scale in 0.5 dB(A) steps from 60 to 75 dB(A).

The general trend of the overall noise levels with log(*speed*) is quite linear, but may individually deviate in specific speed ranges for some EVs.

The **Peugeot e208** (front-motor) has rather balanced contributions of both wheel zones at low speeds, but a slightly higher contribution from the rear wheel beyond 40 km/h. The larger atypical levels on the front wheel zone below 30 km/h are due to the AVAS signal audible towards the vehicle side. The **Renault ZOE** (front-motor) shows higher noise levels from the rear wheel zone by 1-2 dB(A) over most of the speed range, except above 85 km/h where wheel zone contributions are balanced. The **BMW i3** (rear-motor) offers a balanced wheel zone contribution on almost the entire speed range. The **Nissan LEAF#1** (front-motor) has very unequal inputs, with a quite stronger contribution from the rear wheel zone by about 4 dB(A) at most speeds, except between 60-80 km/h with a lower difference. The **Tesla Model 3** (dual-motor) shows an increasingly higher contribution of the rear wheel zone with increasing speed. The motors management is not known, but at constant speed where the power demand remains low, one of the motors might be preferred due to own performance. The **Renault Kangoo ZE** (front-motor) has a balanced contribution from both wheel zones at all speeds.

When comparing the wheel zones of all vehicles, the rear wheel of the Nissan LEAF#1 and the Renault ZOE differentiate by a significantly higher level at most speeds, at least over urban speed range (Figure 5). Then comes the ZOE front wheel, confirming this vehicle as the least quiet one on this road surface among the vehicles tested, in accordance with the CPB results in [3]. Other wheel zones and vehicles are fairly clustered, with moderate spread at urban speed.

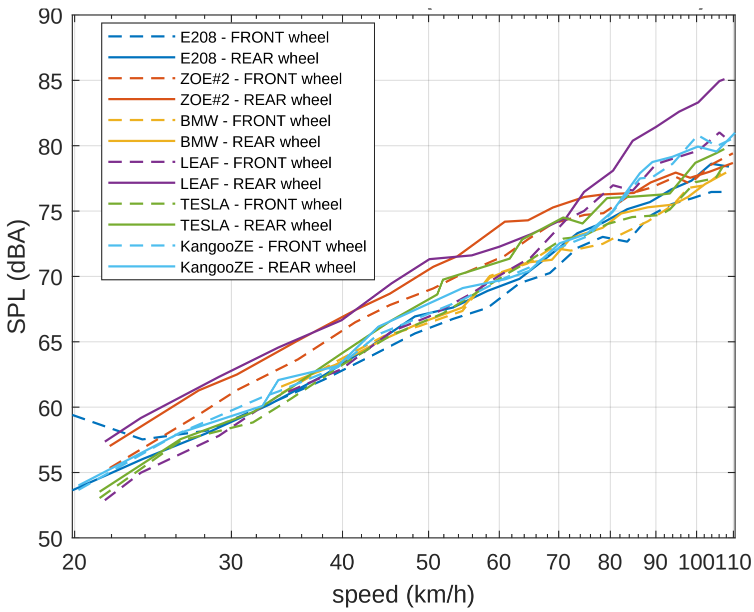

Figure 5: Contribution of the front wheel zone (resp. rear wheel zone) of the EVs as a function of speed on road surface N – A-weighted noise levels in the range [100 - 5000 Hz] at the reference distance of 2.7 m.

3.2. Variable speed

It is to be expected that noise source ranking changes at driving modes with variable speed, due to modified contributions of motor noise and of tyre/road noise, the latter resulting from increased forces in the contact area [8].

Because of different motor performance, the acceleration rates vary from one vehicle to another, the Tesla Model 3 having the highest acceleration ability and the Kangoo ZE the lowest one among the set of vehicles tested. In addition, the higher the instantaneous speed, the lower the acceleration for any vehicle. The main observation under vehicle acceleration relates to the significant increase of the contribution from the driving wheel areas.

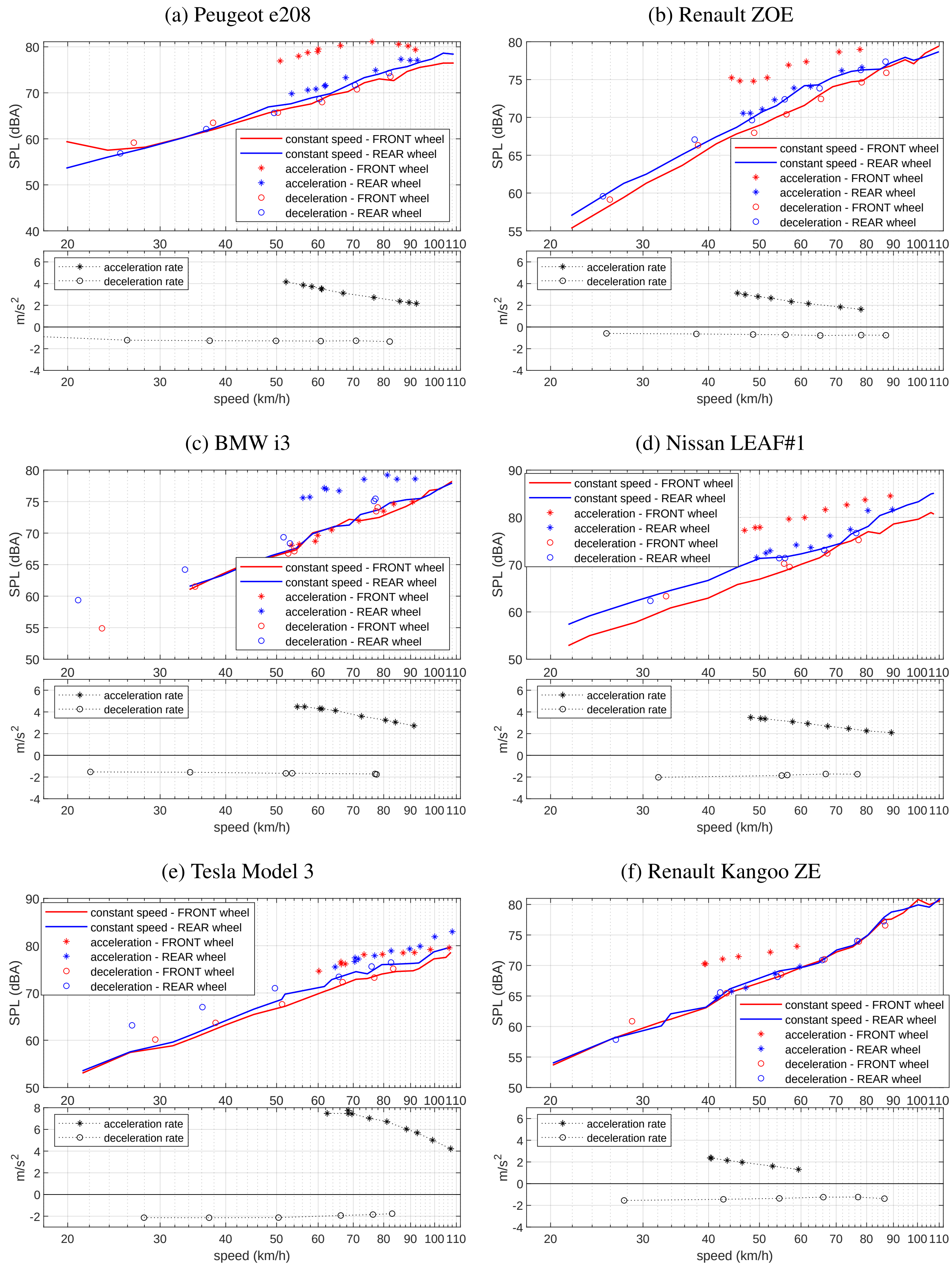

Figure 6: Front and rear wheel noise sources of the EVs in all driving modes on road N – For each EV, *Top*: A-weighted overall noise levels at the reference distance of 2.7 m – *Bottom*: acceleration and deceleration rates

Figure 6 superposes the contributions of each wheel zone measured respectively at constant speed, under full acceleration and under deceleration, as a function of instantaneous speed right to array centre, for each vehicle tested. In addition, it plots the acceleration (resp. deceleration) rates recorded at each pass-by.

Relatively to constant speed conditions, the accelerating vehicles with front-motor and front-wheel drive show a significant increase of the noise radiation from the front wheel zone, which becomes on any such EV the dominating noise source. The growth of noise from this area generally exceeds 5 dB(A) around 50 km/h and reduces with decreasing acceleration rate at higher speeds to about 4 dB(A) around 70-80 km/h (respectively around 60 km/h for the Renault Kangoo ZE having a lower acceleration ability). This comes from medium frequencies 500-1600 Hz with a suspected enhancement from tyre components, but also quite uniformly in the high frequency bands. By contrast, the contribution from the rear wheel zone is unchanged for the Renault Kangoo ZE, almost unchanged for the Renault ZOE, but with a slight increase still to be explained for the Nissan LEAF and the Peugeot e-208. The same behaviour is observed with the rear-wheel drive BMW i3 by just reversing the roles of front and rear wheel zones. Finally, the dual-motor Tesla Model 3 with four-wheel drive spreads the effect of acceleration on noise emission between the two axles, in a quite reasonable degree in view of the strong acceleration rates.

In the deceleration tests without use of the brake, the motor is used as a generator for energy recovery from the loss of kinetic energy. Depending on vehicle, deceleration rates range from moderate (-0.6 m/s2 for ZOE) down to higher (-2.1 m/s2 with Model 3). For every car, deceleration remains relatively constant over the speed range. When compared to constant speed conditions, deceleration has no acoustical effect on overall sound emission from non-drive wheel zones of any vehicle. Its effect on drive wheel noise emission remains low, not greater than 1-2 dB(A), and only at speeds below 40-50 km/h for Kangoo ZE, LEAF#1, ZOE and e-208. The EVs that clearly stand out in this driving condition are:

- the BMW i3, showing an increase of noise emission from the drive-wheel zone over the whole speed range tested and estimated to about 5 dB(A) at low speed and lowering to 1.5 dB(A) over 20-80 km/h,
- the Tesla Model 3 below 50 km/h, for which noise increase mainly comes from the rear wheel zone and is assessed to 5.5-2.5 dB(A) according to speed.

4. EFFECT OF LOW-NOISE ROAD SURFACES ON EV NOISE SOURCES

The approach followed for exploring the noise sources of the vehicles driving on the prototype road surfaces P and PCR is fully identical to that described previously and the results are given according to the same pattern. The analysis is focused on three EVs: Renault ZOE, Nissan LEAF and Kangoo ZE. The three vehicle tested are front-wheel driven, with the electric motor located close to this area. It should be pointed out that the use of a different Nissan LEAF makes irrelevant a direct comparison of the noise sources identified on road surfaces P/PCR with those on N. Also, a material problem introduced uncertainty into the ZOE results on PCR, and they are discarded as a precaution.

4.1. Constant speed

For an overview at all speeds on road surfaces N, P and PCR, the noise level at each wheel zone is displayed as a function of speed in Figure 7. As a general overview, when comparison is possible, it turns out that both prototype road surfaces compared with road N bring an overall noise reduction from both wheel zones at all speeds. The ranking of one prototype over the other is not clear and may vary according to frequency. In more details:

- ZOE: at 50 km/h, as well as at all speeds, the prototype road surface P brings noise reduction from wheel zones compared to road N, estimated between 1 and 3 dB(A) depending on speed.

The rear one (non driving wheel) remains the louder. The general behaviour is similar in frequency, with a relatively uniform noise reduction across all frequency bands.

- LEAF#2: although LEAF#1 and LEAF#2 cannot be readily compared, the strong predominance of the rear wheel zone (non driving wheel) is a common feature on both vehicle versions at any speed, even greater on LEAF#2. At 50 km/h, this is mainly due to contributions in the 500 Hz and 1 kHz third-octave bands, but shifting in frequency with speed and strongly prominent on the rear wheel. There is no significant overall noise level difference between prototypes P and PCR.

- Kangoo ZE: both wheel zones have a different balance on road N or on P/PCR at 50 km/h, the front wheel being the noisier in the latter case and prevailing in the 630 Hz third-octave. The prototype test sections provide a clear noise reduction from the rear position at all speeds, the decrease is lower but effective from the front one. More generally, test sections P and PCR introduce a reduction over test section N above 800 Hz, but the opposite is true below 630 Hz.

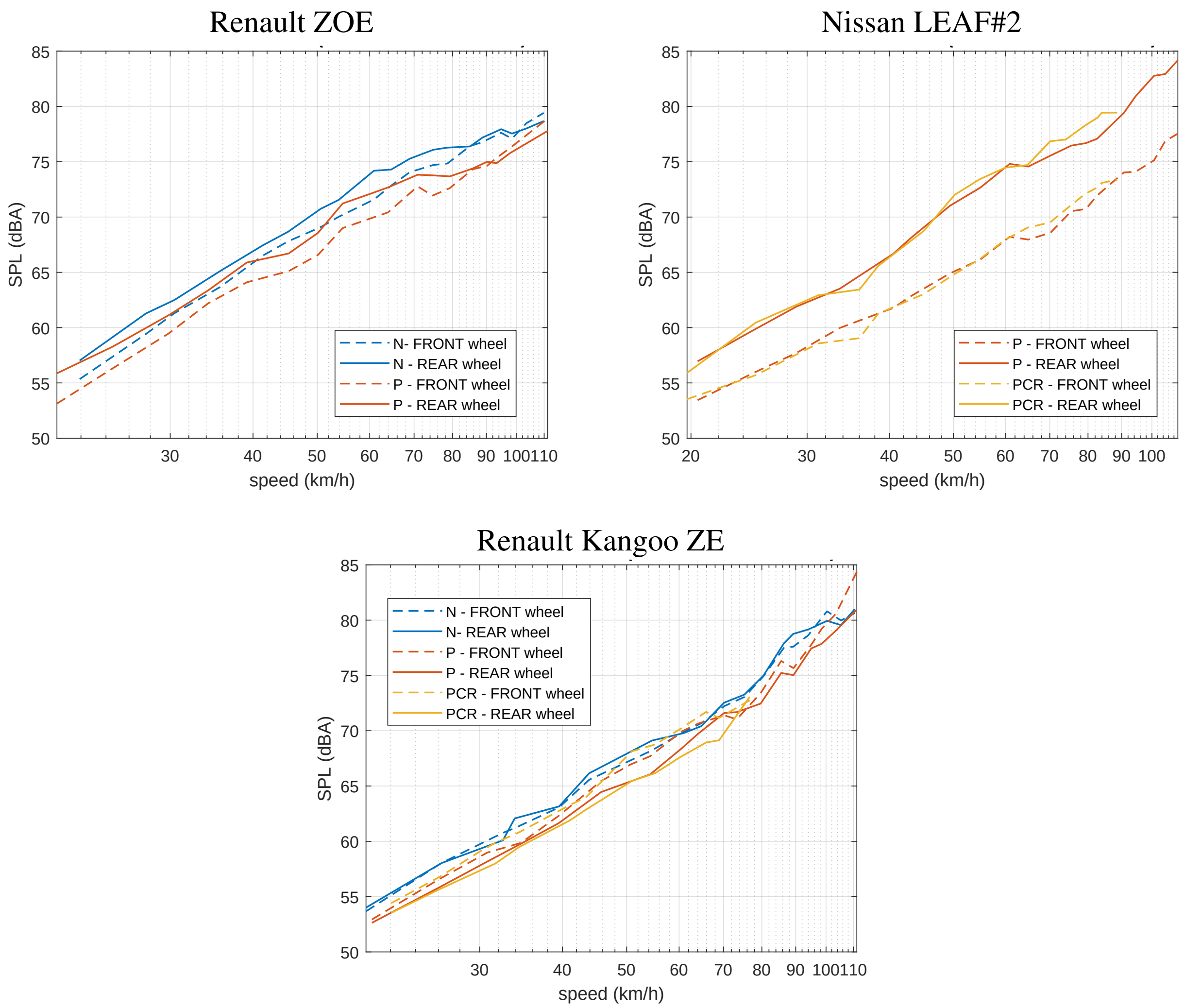

Figure 7: Contribution of the front wheel zone (resp. rear wheel zone) of the EVs at constant speed on road surfaces N, P and PCR – A-weighted noise levels in the range [100 - 5000 Hz] at the reference distance of 2.7 m.

4.2. Variable speed

Compared to constant speed pass-bys of Figure 7, the acceleration condition strongly increases the contribution from the front wheel zone of the Renault ZOE and the Renault Kangoo ZE (Figure 8). This increase from the front wheel remains more moderate with the Nissan LEAF#2, despite its acceleration capacities, and the rear wheel zone is continuously dominating at all speeds. Considering the Kangoo ZE, the contribution of its rear wheel zone is unchanged with acceleration, and the front one increases by about 3 dB(A) in the range 40-60 km/h.

When comparing the three road surfaces N, P and PCR for each vehicle under full acceleration:

- ZOE gives lower noise levels on prototype test section P than on test section N at all speeds up to 90 km/h, for both wheel zones, with a stronger reduction on the front wheel zone which is the dominant one. The reduction is significant at frequencies beyond 800 Hz.
- LEAF#2 shows no significant noise level difference between both prototype road surfaces P and PCR, both overall and in frequency.
- The two prototype test sections bring a noise level decrease from both wheel zones of the Kangoo ZE compared with test section N. This can be estimated from -1 to -2.5 dB(A) between N and P on the rear wheel zone (resp. 0 to -3 dB(A) on the front one). In frequency the noise levels with P grow relative to N up to 630 Hz, while they decrease above 800 Hz.

In accordance with the observations made on the CPB results with the decelerating vehicles [5], no significant effect of deceleration at pass-by relatively to constant speed was noticed and the noise sources are not investigated further in this driving condition on P and PCR.

5. CONCLUSIONS

In the LIFE E-VIA project for the control of rolling noise emission from light electric vehicles, the noise sources of a set of six EVs driving on a smooth ISO-like road surface have been investigated. At vehicle pass-by the area close to both wheels and wheel-road contact patches are the noise main sources. The contribution from these two zones at constant speed differ according to vehicle, but if not balanced, there is a general trend of a higher contribution from the rear wheel, regardless the position of the motor and driving wheel. This is most noticeable with Renault ZOE and Nissan LEAF, particularly at urban speeds. Under full acceleration, the driving wheel zone has a greatly increased role (about 5 dB(A) at 50 km/h) and becomes dominant. Only the Tesla Model 3 fitted with a motor at front and rear positions has a lower but shared increase on both wheels areas, which are noise balanced. Regenerative braking has a weak acoustical impact on the driving wheel contribution (nearby motor, torque at contact area) confined to low speeds, apart for the BMW i3 and Tesla Model 3 with an increase up to 5 dB(A).

The investigations then focused on a selection of three EVs driving on the low-noise road surface prototype developed by the project in two versions, one without and the other with crumb rubber. When comparison with the previous tests was possible, noise source reduction by the prototype road surfaces could be observed on both wheel zones, with no significant discrepancy or uniform trend differentiating the two prototype versions. At constant speed, the rear wheel contributions of Renault ZOE and Nissan LEAF remain predominant, whereas this was reversed with the Renault Kangoo ZE. Under full acceleration, the front wheel area has again the highest role for Renault ZOE and Kangoo ZE, but despite front increase on the Nissan LEAF the rear one remains clearly prevalent. In all cases, the noise source reduction introduced by the low-noise prototypes generally occurs at frequencies above 800 Hz.

The differences between vehicles and road surfaces together with driving conditions highlight a diversity of noise source behaviours, which result from complex and yet to be deepened combined

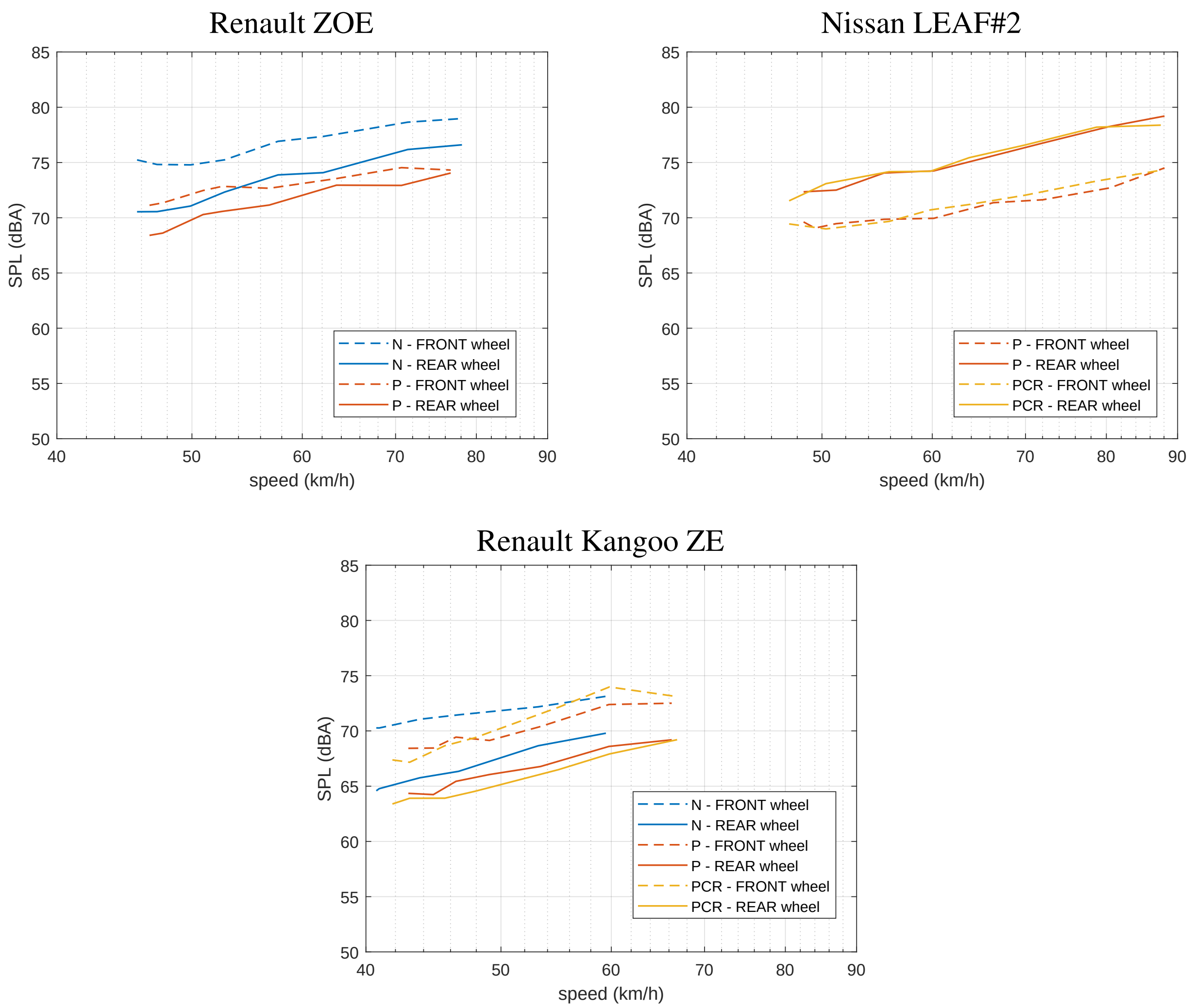

Figure 8: Contribution of the front wheel zone (resp. rear wheel zone) of the ZOE (top left), the LEAF#2 (top right) and the Kangoo ZE (bottom) under full acceleration, on road surfaces N, P and PCR – A-weighted noise levels in the range [100 - 5000 Hz] at the reference distance of 2.7 m.

effects of tyre compounds and tread pattern design, road surface properties (3D-texture, absorption), radiation characteristics through geometric configuration (horn effect, bodywork shape), as well as torque effect at the contact area when relevant.

ACKNOWLEDGEMENTS

The authors thank the European Commission for its financial contribution to the LIFE18 ENV/IT/000201 LIFE E-VIA project into the LIFE2018 programme.

This work used measuring equipment of the LABEX CeLyA (ANR-10-LABX-0060) of Université de Lyon, funded within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

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