FOREVER

Impact of low-noise tyres on electric vehicle noise emission

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TRL (Transport Research Laboratory), United Kingdom

Austrian Institute of Technology (AIT), Austria

Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), France

Trinity College Dublin

University of Bath
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Future Operational impacts of Electric Vehicles on European Roads

Impact of low-noise tyres on electric vehicle noise emission

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Author(s) this deliverable:
Sara Gasparoni, AIT (Austria)
Martin Czuka, AIT (Austria)
Reinhard Wehr, AIT (Austria)
Marco Conter, AIT (Austria)
Marie-Agnès Pallas, IFSTTAR (France)
Michel Bérengier, IFSTTAR (France)

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Quality Review:

On behalf of the Author’s Institute

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<thead>
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On behalf of the FOREVER Consortium

<table>
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Executive summary

The present document is the final report of Work Package 3 (WP3) of the FOREVER project. The aim of this work package was to investigate potential and dedicated tyres currently used for electric vehicles and their noise output. While Work Package 2 (WP2) takes care of the overall noise emitted by electric and hybrid vehicles, WP3 focusses on the noise emitted by the tyre-road interaction. This particular component of the overall emitted noise has been analysed for a long time, but now, the almost complete absence of motor noise makes measurements of this component also possible at lower speeds.

A tyre selection has been performed in order to represent the current market of tyres for electric and hybrid vehicles. As shown by the literature study carried out within task 3.1, the selection of tyres for electric vehicles by car and tyre manufacturers is currently driven by fuel resp. energy efficiency requirements, relying on the rolling resistance performance of the tyre. No relation is currently present between rolling resistance and rolling noise. There is currently no evidence of a trend between the rolling resistance performance and the EU rolling noise labels.

Using the selected tyres controlled pass-by measurements according to ISO 11819-1 have been performed, and the results have been analysed. As expected from the literature review, the relation between the overall maximum pass-by noise level in dB(A) and the logarithmic vehicle speed is linear, where the maximum contribution to overall noise is evidently coming from the rolling noise. The maximum spread between two investigated tyres never exceeded 3.6 dB for lower speeds (20 - 50km/h) and for speeds between 50 and 120 km/h the spread never exceeded 2.4 dB.

General similarities in the spectral behaviour could be found in the sample of selected tyres, for example a higher slope of 2 kHz and a lower slope of 500 Hz components to speed in comparison to the most dominant 1 kHz band. So the sample showed not only a changing spectral distribution over speed but also a common behaviour for the tyre sample. The spectra at different speeds give a comparison of occurring peaks and showed the dominance of the 1 kHz octave band.

Additionally, the case studies analysed the differences between the selected tyres in detail. Spectral components can rise differently with speed so the relative difference of the distribution changes. Nevertheless these differences have only little relevance on the overall levels.

Investigations conducted on noise measurements at pass-by of two electric vehicles successively fitted with nine different tyre sets (eight sets on the first vehicle, one set on the second vehicle) did not bring to light any relation between the exterior noise EU-label and the noise on actual road surfaces, in particular regarding tyre ranking. This has impacts on the concept of low-noise tyres since a possible requirement on the limit value based on the EU-label would not lead to select the quietest tyres on actual dense road surfaces and would probably not modify the roadside traffic noise.

Tyres designed or selected by manufacturers for EVs have no effect on global rolling noise compared to conventional tyres. A wider set of EV-specific tyres is required to conclude on frequency differences possibly impacting the roadside traffic noise.

On the basis of current knowledge, it turns out that rolling noise from light electric vehicles does not differ from conventional vehicles. Thus, for predictions of traffic noise according to the European assessment method, the use of the rolling noise component given in CNOSSOS-EU remains available without amendment for light electric vehicles. Only the propulsion noise component requires correction terms, as proposed in the final report of Work Package 2 of the FOREVER project.
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1 Introduction

Electric and hybrid vehicles are increasing steadily in the traffic fleet, thus changing the overall image of traffic. In the case of electric and hybrid vehicles, the propulsion system is producing less noise, thus a different sound emission is expected. The presence of an electric motor in combination with a battery (for e-vehicles) and with an additional combustion engine (for hybrid vehicles) instead of a conventional propulsion system is the main reason for the different noise emitted by such vehicles. Electric cars have been originally developed for urban environments, mainly because of the necessity of recharging them more regularly than refuelling combustion engine vehicles. Research studies during the past years (Garay-Varga, 2010) (Morgan, 2011) (Altinsoy, 2013) (Glaeser, 2014) (Czuka, 2014) were already conducted in order to gain more information on the different acoustic emissions within an urban environment and to consider the safety aspect for pedestrians and for some particular people categories (e.g. visual impaired people). Those studies show that the noise emitted by electric vehicles has a different frequency distribution and can also have a different overall level especially at low speeds when the propulsion noise is dominating the overall noise emission. For this reason the FOREVER project aims to study the noise behaviour of electric and hybrid vehicles with special regards to non-urban surroundings like motorways and national highways. Work Package 3 in particular aims to investigate the tyres currently used for electric vehicles and analyse in more detail their noise emission.

Task 3.1 was performed by AIT and is concerned with the analysis of tyre types used with electric vehicles with regard to their noise performance: in Chapter 2 the results of the market investigation relative to the tyres available at the time when the study started are presented. As rolling resistance, wet grip and rolling noise are values declared by the production company in the European tyre label; those parameters were considered in order to select potential and dedicated tyres for electric vehicles for the acoustic measurements planned within task 3.2.

Task 3.2 was performed by AIT and deals with the comparison of noise emission of electric vehicles using different tyres, which is described in Chapter 3. This Chapter deals first with the measurement campaign and the data analysis of the pass-by measurements, which were carried out according to the standard ISO 11819-1. The measurements have been then analysed in terms of overall pass-by levels as well as frequency analysis. In addition, four tyres have been analysed as case studies.

Task 3.3 was performed by IFSTTAR and was mainly dealing with the relation between rolling noise of measured EVs and the European calculation model CNOSSOS-EU. In Chapter 4 a comparison of the measurement results with the EU noise labels was carried out. After that, in Chapter 5 the pass-by noise measurements were compared with the CNOSSOS-EU prediction model in order to consider the relevance of corrections for the rolling noise component. More details on the CNOSSOS-EU model for electric vehicles (also called CNOSSOS-EV) and especially the proposed correction for propulsion noise are available in the FOREVER final report of WP2 (Pallas et al., 2014).

Task 3.4 was originally part of Work Package 3, aiming at modelling tyre-road emission for electrical vehicles. After the findings of the other WP3 tasks, this goal lost its usefulness within this Work Package. For this reason the task has been slightly modified and will take care of the Electrical Vehicles (EV) level correction factors. As this issue becomes a more qualitative than quantitative nature, this task was moved to Work Package 4, which is dealing with the estimation of the potential noise impacts of electric vehicles.

As conclusion of the present work Chapter 7 summarises the main findings of WP 3.
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2 Literature survey/analysis of tyre types used with electric vehicles with regard to their noise performance

2.1 Introduction

In Europe the traffic noise is by far the most important noise source. Figure 1 shows, for example, the people distribution regarding noise exposure levels in agglomerations and for Europe in total, as reported in the CEDR report “Value for money” (Milford, 2013). The noise produced on the traffic routes is dependent on the adopted noise mitigations measures (e.g. low noise pavements or noise barriers), the composition of the vehicle fleet, the used tyres within the fleet and the used road surfaces. The introduction of electric vehicles (EV) in the fleet has the potential to change the noise emitted by road traffic, due to the strongly reduced propulsion noise, that makes electric vehicles intrinsically quieter at urban speeds (Czuka et al., 2014) (Pallas et al., 2014). The potential use of different dedicated tyres for electric vehicles (EV) could also contribute to different noise emission.

![Figure 1: Distribution of people in the noise bands in agglomerations and for Europe in total (source: Milford, 2013).](image)

In order to reduce the rolling noise, two new regulations were introduced by the European commission that replace the directives 2001/43/EC that had been used previously. These new regulations are the EU regulation (EC) No 661/2009, in which the new thresholds for the type approval of the new tyres are established and the EU regulation (EC) No 1222/2009, in which the characterization of the new tyres is defined. According to this regulation, 6 different categories (A, B, C, E, F, G) have been introduced for wet grip and rolling resistance, where A stands for the better values (lower rolling resistance and higher wet grip). A third parameter concerns exterior noise emission, combining noise level values and a three-level pictogram.


2.2 Statistics of tyres

In the frame of task 3.1 an analysis of the tyres available in the market considering the EU tyre label values has been conducted. In order to choose suitable and available test tyres for the measurements planned in task 3.2 a set of 1697 car tyres of different dimensions have been taken into account, sometimes the same tyre-type can appear several times in the list with different indexes of speed or dimensions. A summary of the car tyre dimensions used for the statistics can be seen in Table 1.

Table 1: Summary of the tyre dimensions used in the statistics.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Number of tyres</th>
</tr>
</thead>
<tbody>
<tr>
<td>165-70-R14</td>
<td>76</td>
</tr>
<tr>
<td>185-60-R15</td>
<td>135</td>
</tr>
<tr>
<td>195-55-R15</td>
<td>122</td>
</tr>
<tr>
<td>195-65-R15</td>
<td>276</td>
</tr>
<tr>
<td>205-55-R16</td>
<td>425</td>
</tr>
<tr>
<td>205-60-R16</td>
<td>164</td>
</tr>
<tr>
<td>215-60-R16</td>
<td>109</td>
</tr>
<tr>
<td>225-45-R17</td>
<td>314</td>
</tr>
<tr>
<td>245-45-R19</td>
<td>38</td>
</tr>
<tr>
<td>275-40-R19</td>
<td>38</td>
</tr>
</tbody>
</table>

Figure 2 to 4 show the distribution of the label values for the three parameter rolling resistance, rolling noise and wet grip for the chosen tyres’ dimensions.

Regarding rolling resistance, there is an accumulation towards values with high rolling resistance (labels E to G). It is interesting to note here that the category “G” of the rolling resistance label is above the threshold value CR ≤ 12, defined in the EU regulation 2009/661/EG. In this category you find in the here presented statistical analysis 53 tyres (3.1%). In comparison to this, in the category “A” you find actually 10 tyres (0.6%) and in the category “B” 111 tyres (6.5%).

For the wet grip the situation is radically different (Figure 3). In the category F, which does not fulfil the threshold condition, there are 5 of 1697 tyres, in the category A there are 152 tyres (representing 9.0% of the total) and in the category B 612 tyres (representing 36% of the total) showing that the focus of the tyre producers is mainly on the safety parameters.

If you concentrate on the distribution of the rolling noise of the single tyres (Figure 4) you will see that for the prevalent dimensions an approximated normal distribution centred on the threshold value for each tyre type can be recognized. A spread of about 11 dB for the tyres available in the market can be seen. 1190 of the observed tyres (representing 70.1% of the total) are under respectively on the threshold value defined in the EU regulation 2009/661/EG, and about one third (507 tyres, 29.9% of the total) are over the threshold value.
Figure 2: Distribution of the label values of the rolling resistance for chosen tyre dimensions.
Figure 3: Distribution of the label values of the wet grip for chosen tyre dimensions.
Figure 4: Distribution of the label values of the rolling noise for chosen tyre dimensions (red line: threshold value defined in Regulation 1009/661/EG).

Figures 5 to 7 show the values of the labels relatively to the selling price. It is possible to see a minimal influence of the values on the actual price. Especially for the rolling noise property the price decrease is only visible for the tyres whose values lie above the threshold values given by the EU regulation 2009/661/EG.
Figure 5: Statistical distribution of the selling price in each rolling resistance subclass for chosen tyre dimensions.
Figure 6: Statistical distribution of the selling price in each rolling noise sub-class for chosen tyre dimensions.
Figure 7: Statistical distribution of the selling price in each wet grip sub-class for chosen tyre dimensions.

Figure 8 to Figure 10 show the density spread functions of the label parameters. It is possible to see the strong role played by the average values, but either a correlation between the tyre properties or a special trend, as initially expected, cannot be seen.
Figure 8: Density spread function rolling resistance-wet grip for the chosen tyre dimensions. Note, that the intervals between two neighbouring ratings of the rolling resistance and the wet grip have not the same size.
Figure 9: Density spread function rolling resistance-rolling noise for the chosen tyre dimensions. Note, that the intervals between two neighbouring ratings of the rolling resistance have not the same size.
Figure 10: Density spread function rolling noise-wet grip for the chosen tyre dimensions. Note, that the intervals between two neighbouring ratings of the wet grip have not the same size.

Table 2 shows the results of the regression analysis of the three label values with the selling price. Even if the regression line has the expected inclination (a tyre in the next worse category is cheaper than the other) still the indefiniteness is so high that practically no correlation exists. Apparently the labelling has not been used so far as a motivation to selling. Note that the intervals between two neighbouring ratings of the wet grip and the rolling resistance classes have not the same size.
Table 3 describes the situation making use of the parameters of the regression analysis. There is clearly no correlation between these parameters.

### Table 2: Coefficients for the regression analysis of the tyre label values against the selling price.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Inclination Rolling noise</th>
<th>R² Rolling noise</th>
<th>Inclination Wet grip</th>
<th>R² Wet grip</th>
<th>Inclination Rolling resistance</th>
<th>R² Rolling resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>165-70-R14</td>
<td>-0.25</td>
<td>0.04</td>
<td>0.25</td>
<td>0.01</td>
<td>-4.24</td>
<td>0.86</td>
</tr>
<tr>
<td>185-60-R15</td>
<td>-3.33</td>
<td>0.81</td>
<td>-4.77</td>
<td>0.68</td>
<td>-2.62</td>
<td>0.68</td>
</tr>
<tr>
<td>195-55-R15</td>
<td>-2.37</td>
<td>0.66</td>
<td>-12.46</td>
<td>0.95</td>
<td>-5.52</td>
<td>0.94</td>
</tr>
<tr>
<td>195-65-R15</td>
<td>-0.93</td>
<td>0.45</td>
<td>-3.86</td>
<td>0.86</td>
<td>-3.04</td>
<td>0.98</td>
</tr>
<tr>
<td>205-55-R16</td>
<td>-1.45</td>
<td>0.38</td>
<td>-4.15</td>
<td>0.80</td>
<td>-0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>205-60-R16</td>
<td>-4.96</td>
<td>0.79</td>
<td>-6.69</td>
<td>0.46</td>
<td>-8.24</td>
<td>0.83</td>
</tr>
<tr>
<td>215-60-R16</td>
<td>-7.24</td>
<td>0.76</td>
<td>-5.64</td>
<td>0.23</td>
<td>-10.67</td>
<td>0.92</td>
</tr>
<tr>
<td>225-45-R17</td>
<td>-1.46</td>
<td>0.12</td>
<td>5.23</td>
<td>0.34</td>
<td>2.34</td>
<td>0.38</td>
</tr>
<tr>
<td>245-45-R19</td>
<td>-18.07</td>
<td>0.67</td>
<td>-6.25</td>
<td>0.37</td>
<td>-3.82</td>
<td>0.26</td>
</tr>
<tr>
<td>275-40-R19</td>
<td>-9.15</td>
<td>0.37</td>
<td>-10.21</td>
<td>0.85</td>
<td>-5.33</td>
<td>0.31</td>
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</tbody>
</table>

### Table 3: Coefficient of determination of the correlation analysis between the different tyre parameters.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>R² Rolling resistance/ Wet Grip</th>
<th>R² Rolling Resistance/ Rolling Noise</th>
<th>R² Wet Grip/ Rolling Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>165-70-R14</td>
<td>0.18</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>185-60-R15</td>
<td>0.13</td>
<td>0.02</td>
<td>0.17</td>
</tr>
<tr>
<td>195-55-R15</td>
<td>0.08</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>195-65-R15</td>
<td>0.28</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>205-55-R16</td>
<td>0.09</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>205-60-R16</td>
<td>0.10</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>215-60-R16</td>
<td>0.18</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>225-45-R17</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>245-45-R19</td>
<td>0.15</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>275-40-R19</td>
<td>0.16</td>
<td>0.00</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Regarding the choice of tyres for the measurement campaign in Task 2.3, by this market study no correlation between the tyre properties could be found. It cannot be concluded that tyres possessing a low rolling resistance, as expected to be used for electric vehicles, also possess a low rolling noise tyre label value. In the next section more specific tyres dedicated to the electric vehicles will be considered in more detail.
2.3 Tyres for electric and hybrid vehicles

The considerations so far were very general and have taken into account the actual market, without focusing specifically on electrical and hybrid vehicles.

As we started considering electric and hybrid vehicles, energy considerations have been taken into account. Considering the charge limitation of electric vehicles, a particular focus has to be placed on the low rolling resistance of the tyres. Lower rolling resistance implies less dissipated energy and thus a longer usage of the battery charge. Of course safety considerations also play a fundamental role. Thus the set of tyres that we will analyse and use for the test drives are tyres with a low rolling resistance with a secondary focus on high wet grip.

After the introduction of electric and hybrid vehicles in the traffic channels, some tyre producers started designing specially tailored tyres for this niche. In the following, the usual notation for the dimensions of tyres will be adopted. For example in 205/55 R16, 205 corresponds to the width of the tyre in mm, 55 to the aspect ratio of the tyre (the height of the cross-section expressed as a percentage of its width) and 16 for the rim diameter in inches.

The tyre producer Michelin produced specifically for the electric vehicle Renault ZOE the tyre ENERGY E.V.

The tyre producer Continental introduced the tyre Conti.eContact, which has innovative new tyre dimensions, such as 195/55 R20 instead of a traditional 205/55 R16. This concept results in substantially reduced rolling resistance (30% less than normal tyres). Thanks to the larger tyre diameter, deformation of the tyre is reduced when entering the contact patch, thus lowering rolling resistance considerably. Tyres with dimensions 125/80 R13M and 145/80 R13M have been produced, but they are still too thin to be used with bigger cars like Renault Fluence Z.E.. Tyres of dimensions 195/55 R20T have been planned but have not been built yet. Because of the limited size range we will not use these innovative tyres within this project.

In March 2010 the tyre producer Goodyear launched the EfficientGrip prototype tyre for electric and hybrid vehicles – specifically developed to fulfil the distinctive requirements of future electric vehicles. The design of the concept tyre was originally meant to complement the performance requirements of electric vehicles. Later on the tyre has also been used for non-electric cars, and as such it is not any more considered as a tyre specific for e-vehicles. The tyre’s narrow shape in combination with a large diameter leads to reduced rolling resistance levels and to a reduced aerodynamic drag and thus reduced energy consumption.

Electric engines often provide a relatively constant torque, even at very low speeds, which increases the acceleration performance of an electric vehicle in comparison to a vehicle with a similar internal combustion engine. This required the development of a modified tread design in combination with a new tread compound to ensure better grip especially on dry roads, and to provide high levels of mileage.

The Goodyear Efficient Grip with the dimensions 205/55 R16 is normal equipment for the electric car Renault Fluence Z.E. and will therefore be one of the tyre types used for the measurements (since a Fluence will be used as the test vehicle).

As there are not many products on the market specifically tailored for electric and hybrid vehicles, we chose the tyres with the best rolling resistance. Two of them (Goodyear efficient grip and Toyo NANOENERGY) are in the category A for rolling resistance, the others will be chosen in the category B for rolling resistance, taking care that different tyres of different
producers are tested and that the technical limitations of the car are respected (tyre size as in the car’s licence).

Based on the market study described in chapter 2 the test tyres were chosen. In the analysis the short form (A-H) from Table 4 is used to distinguish the tyres. Additionally to the eight tyres selected based on the market study, one more tyre has been added, the Michelin Energy E-V. In the following documentation this tyre will be denominated tyre I. This tyre is particularly interesting because it has been exclusively produced for electric vehicles, specifically for the Renault ZOE, which was the vehicle used during the additional measurement campaign.

Table 4: Set of tyres chosen for the measurements. The EU label is in the format Rolling Resistance / Wet Grip / Noise Emission.

<table>
<thead>
<tr>
<th>Short form</th>
<th>Brand</th>
<th>Model</th>
<th>Dimensions</th>
<th>EU Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Dunlop</td>
<td>Sport BluResponse</td>
<td>205/55</td>
<td>R16 91H</td>
</tr>
<tr>
<td>B</td>
<td>Goodyear</td>
<td>Efficient Grip</td>
<td>205/55</td>
<td>R16 91H</td>
</tr>
<tr>
<td>C</td>
<td>Kumho</td>
<td>Ecowing ES 01 KH27</td>
<td>205/55</td>
<td>R16 91V</td>
</tr>
<tr>
<td>D</td>
<td>Pirelli</td>
<td>Cinturato P1 Verde</td>
<td>205/55</td>
<td>R16 91H</td>
</tr>
<tr>
<td>E</td>
<td>Toyo</td>
<td>NANOENERGY 2</td>
<td>205/55</td>
<td>R16 91V</td>
</tr>
<tr>
<td>F</td>
<td>Bridgestone</td>
<td>Ecopia EP150</td>
<td>205/55</td>
<td>R16 91H</td>
</tr>
<tr>
<td>G</td>
<td>Michelin</td>
<td>ENERGY SAVER</td>
<td>205/55</td>
<td>R16 91W</td>
</tr>
<tr>
<td>H</td>
<td>Hankook</td>
<td>Kinergy Eco K425</td>
<td>205/55</td>
<td>R16 91H</td>
</tr>
<tr>
<td>I</td>
<td>Michelin</td>
<td>ENERGY E-V</td>
<td>195/55</td>
<td>R16 91Q</td>
</tr>
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</table>
3 Measurement and analysis of low-noise tyres

In this chapter the results of the pass-by measurements are presented. After the description of the set-up, the performance of the tyres with regard to each other is discussed in 3.2. Here the focus is not only on the overall level, but also on the spectral changes due to different speeds. Afterwards, four case studies of tyres (3.3) are presented, which are a good representation of the overall behaviour in the previous analysis.

3.1 Measurement set-up

Tyre-road noise produced by an electric vehicle has been analysed by controlled pass-by measurements (CPB). The measurement set-up is as close as possible to common standards on vehicle noise. (ISO 11819-1, 2002), (UN Reg. 117, 2014).

Measurements were taken between summer and fall 2013. The method used was based on the determination of the maximum A-weighted sound pressure level (L_AFmax) during the run of a test vehicle at steady speed on asphalt pavement.

\[
L_{AF\text{max}} = 10 \log_{10} \left( \frac{p_{AF\text{max}}^2}{p_0^2} \right) \text{ in dB(A)}
\]

Figure 11 shows the measurement set-up. Four test tyres have to be mounted on the vehicle that drives with constant speed from C to C’ on the test pavement. The microphone is at point P and is positioned 7.5 m far away from the line C-C’, its height is 1.2 m from the ground. The test surface has to be at least 20 m long (from A-A’ to B-B’). The track is located between two fields, so the criterion of similar sound absorbing material up to 3.75 m to the microphone position P is not completely fulfilled. This is not a problem, because this task focuses on relative differences between the tyres and not absolute values. Calibration of the microphones was performed before and after the measurements.

For the analysis the sound pressure level L_AF was used, depending on the analysis as overall level or in octave bands and quarter tones for detailed spectral analysis. All sound pressure levels were normalised to a reference air temperature of 20°C as used in the CNOSSOS-EU model (CNOSSOS-EU (2012)):

\[
L_{AF}(20^\circ C) = L_{AF}(T) + 0.08 \text{ dB(A)/}^\circ C \cdot (T - 20^\circ C)
\]
The electric vehicle we used is the Renault Fluence Z.E., which is owned by AIT mobility department, and is a better candidate than normally used city-car-sized vehicles for national highways as it is a C-segment car, according to the European car size classification.

The test track chosen is a test track with asphalt AC11, which allows for a good logistic, as the test site was 30 km away from the AIT head quarter. It is important to note that the car battery lasts about 130 km when it is fully charged.

Before each measurement, tyres have been warmed up for about half an hour in order to reach standard working conditions. The tyre pressure was also kept constant over the whole measurement campaign.

It should be mentioned that in the case of tyre I (see Table 4) the following parameters were different:

- The used car was the Renault ZOE (B-segment car, according to the European car size classification), which is substantially smaller than the Renault Fluence Z.E. (C-segment car).
- The used tyres in this case (195/55 R16) have different dimensions compared to the other measured tyres (205/55 R16). This is also connected to the smaller car and the special design for electric vehicles of this tyre.
- The test track was different, and thus also the allowed maximum speeds. This is due to the fact that this extra measurement was done within the frame of an additional measurement campaign. The road surface of the two measuring tracks was in both cases asphalt concrete with 11 mm chipping size (AC11) and the surface between microphones and noise source were in both cases vegetated and from an acoustic point of view comparable.

Together with the A-weighted maximum noise level, also the air and road surface temperature, the wind velocity, and the car speed were measured. Following the rules of ISO 11819-1 (2002) temperature and wind have to be apt for the measurement.

Measurements have been taken for velocities from 10 km/h up to 130 km/h. It is expected that the overall noise is very low for measurements at very low speeds, and the background noise could be indistinguishable from the pass-by-noise. On the other hand, the upper limit of the measurement has been chosen because of safety considerations.
For the speed measurement the GPS of the built-in navigation system of the car has been used to give accurate values.

3.2 Results of the pass-by measurements

Pass-by measurements with electric vehicles at low speeds have high demands on the background noise. We analysed each measurement by hand to check if it fulfils a 10 dB or a 3 dB signal-to-noise ratio criterion. For the final analysis the 3 dB criterion was applied, since even a slight overestimation of the maximum pass-by level (in most cases at low speeds) leads to a regression function, that predicts lower pass-by levels at low speeds compared to the same predictions with a regression function based on a 10 dB selection criterion.

This analysis focuses mainly on the relative difference of the tyres. First the overall sound pressure level is analyzed in regard to speed. Secondly the change of the spectral distribution at different speeds for the various tyres is shown.

3.2.1 Overall sound pressure level

Figure 13 shows the maximum pass-by levels ($L_{A\text{fmax}}$) for all examined tyres after performing a logarithmic regression. Due to the logarithmic scaling of the horizontal axis, the regressions functions appear like straight lines. The coefficients of determination are very high and are listed together with the determined regression equations in Table 5.
Table 5: Results of the logarithmic regression analysis for different tyres including a temperature correction according to equation (2).

<table>
<thead>
<tr>
<th>Tyre</th>
<th>Regression equation</th>
<th>Coefficient of determination ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$L_{AF,max} = 33.36 \cdot \log_{10}(speed) + 11.73$</td>
<td>0.995</td>
</tr>
<tr>
<td>B</td>
<td>$L_{AF,max} = 34.77 \cdot \log_{10}(speed) + 9.30$</td>
<td>0.993</td>
</tr>
<tr>
<td>C</td>
<td>$L_{AF,max} = 36.14 \cdot \log_{10}(speed) + 4.59$</td>
<td>0.997</td>
</tr>
<tr>
<td>D</td>
<td>$L_{AF,max} = 36.21 \cdot \log_{10}(speed) + 4.51$</td>
<td>0.996</td>
</tr>
<tr>
<td>E</td>
<td>$L_{AF,max} = 34.04 \cdot \log_{10}(speed) + 8.88$</td>
<td>0.987</td>
</tr>
<tr>
<td>F</td>
<td>$L_{AF,max} = 34.77 \cdot \log_{10}(speed) + 7.98$</td>
<td>0.994</td>
</tr>
<tr>
<td>G</td>
<td>$L_{AF,max} = 34.10 \cdot \log_{10}(speed) + 9.20$</td>
<td>0.999</td>
</tr>
<tr>
<td>H</td>
<td>$L_{AF,max} = 34.26 \cdot \log_{10}(speed) + 8.00$</td>
<td>0.998</td>
</tr>
<tr>
<td>I</td>
<td>$L_{AF,max} = 36.51 \cdot \log_{10}(speed) + 4.02$</td>
<td>0.989</td>
</tr>
</tbody>
</table>

No measurement fulfilled the signal-to-noise criterion at 10 km/h, the lowest speed is 12 km/h for tyre I. At 19 and 20 km/h measurements for four tyres are available. The biggest difference between the loudest and quietest tyre for a certain speed is at low speeds. The difference between tyre A and I at 19 km/h is 3.6 dB (note that tyre I was measured on a different test site with a different surrounding). At 66 km/h the tyres have the smallest deviation and the biggest difference of 2.2 dB is between tyre H and B. At higher speeds the deviations increase very slowly and at 120 km/h the biggest difference between tyre H and B is 2.4 dB. This analysis gives an overview of the range of the measured tyres. At higher speeds, that means speeds over 50 km/h where tyre noise is also the relevant noise factor for internal combustion engine powered cars, the tyres are less than 2.5 dB apart. At lower speeds the difference tends to be more.

As we see in Figure 13, speed is a relevant factor for the sound pressure level and the tyres behave in a slightly different way. To give a better understanding of this behaviour another form of graph is presented, which can also be found in (Sandberg & Ejsmont, 2002). In Figure 14 the coefficients of the regression analysis are plotted. From this graph the general behaviour of the tyres can be derived with a much better overview over all nine samples and better distinction between the samples.
Figure 14: Regression coefficients of the overall sound pressure level. The dotted line shows a typical slope in the comparison of various tyre samples.

If a tyre has a high slope B and a small intercept A in the regression equation and is therefore located in the right lower corner, it is very quiet at low speeds but the sound pressure level will rise strongly with higher speeds. The sound pressure level of tyres in the upper left corner with a high intercept and low slope is higher at low speeds, but doesn’t rise as much for higher speeds. In short, a measured tyre closer to the upper left corner is better for higher speeds, a measured tyre closer to the lower right corner is better for lower speeds in regard to noise emission. If both intercept and slope are high, the sound pressure level will generally be high, the opposite accounts for low coefficients. So the distance to the lower left corner gives an impression of the overall loudness, which is the reason why both axes span the same interval of 10.

The dotted line in Figure 14 depicts the linear equation $A = 76 - 1.94 \cdot B$ and shows nearly a linear regression of the tyre samples we measured. The factor 1.94 for the slope is derived from the Tyre/Road Noise Reference Book (Sandberg & Ejsmont, 2002) for measurements of mostly passenger car tyres on dense concrete asphalt, which were measured with the drum method. Therefore the mentioned value of 101 in (Sandberg & Ejsmont, 2002) for the intercept of this linear equation is too high for the CPB method with a far way microphone and is manually adapted to the value 76 for a good fit to our tyre sample. Nevertheless the measurements show a typical relationship between tyre samples.

- The samples B, E, F, G and H are very close in the coefficients but have an interesting relationship. E, G and H have nearly the same slope, but a different intercept. So H will be quieter than E, which will always be quieter than G. H has a similar intercept as F. So at speed 1 km/h ($\log_{10}(1) = 0$) this would result in the same sound pressure level. But the higher slope of F makes this tyre generally louder than H. Tyre B has a higher intercept than the tyres E, F, G and H but the same slope as tyre F. So it will be generally and significantly louder as these tyres. B is generally the loudest tyre at high speeds.
• Tyre A is an extreme value with a high intercept and small slope. So it is loud at low speeds, but it increases slowly. So tyre A is the loudest tyre at low speeds, but due to the lower slope it is quieter than tyre B at high speeds.

• Tyre C and D have practically the same regression equation and also tyre I is very close. They have in comparison to the other tyres a high slope and small intercept and perform therefore better at lower speeds and are the quietest tyres at low speeds. But for high speeds the tyres E and H are quieter because of their smaller slope.

After this comparison tyre H is in regard to the overall performance the quietest tyre. Only tyre C, D and I are slightly quieter below (30 km/h), but these are the same amount louder at higher speeds. Tyre A and I are interesting, because they have a complete different behaviour in regard of the speed dependence. Tyre A and B are the loudest tyres of the sample.

3.2.2 Spectral analysis

Detailed analysis

There are different ways to approach the spectral properties of the measurements. The main problem is to show detailed frequency components from nine tyres at up to thirteen different speeds. To resolve this, the linear regression of the sound pressure level to the logarithm of speed is performed in frequency bands. The level of a frequency band for the regression is taken at the point in time at the maximum of the overall level. Now for every frequency band slope and intercept can easily be shown for one tyre per graph, see Figure 15.

Also in this representation the coefficients show a high correlation towards each other. So no frequency component is the same amount louder or quieter as another component for all speeds. That means the spectral distribution changes for different speeds. On the other hand the differences in the intercept are much higher than in the slope, so some frequency components can and will generally be the loudest component over all speeds. But again the different slope will result in a different spectral distribution. A small uncertainty in the determination of the slope of the regression line will result in a large uncertainty on the intercept, since the intercept is the extrapolation of the noise level at a speed located very far from the measurement speed range in a log(speed) scale. For Figure 15 the $L_{AF\text{max}}$ was determined in quarter tones (1/24-octave).

The determined spectrum from the regression analysis at the time of the overall maximum was smoothed with a moving average filter of length four (after the regression analysis), which still gives a detailed spectral resolution of about one whole tone (1/6-octave). This result was used for the whole spectral analysis. In Figure 15 only spectral components with a coefficient of determination higher than 0.9 are plotted, the size of the circles is bigger for correlations closer to 1. For this analysis only measurements which fulfil a 3 dB signal-to-noise ratio criterion in the overall level were used.

The tyres A to H show a more or less similar behaviour, the bigger differences for tyre I are due to the fact that these were additional measurements with different parameters as mentioned before. So this tyre will be excluded from this analysis.
Figure 15: Regression coefficients for spectral analysis for tyres A to H (in quarter tones).
If we analyse the general structure, the following statements can be derived from the relative position of the colour-coded frequency components:

- **Green**: The frequency components of 1 kHz are mostly the loudest components, because they are closest to the upper right corner.
- **Yellow**: 2 kHz components often rise a bit stronger than 1 kHz with speed, but with a significant smaller intercept. Components at 2 kHz are definitely less present at lower speed than for high speeds, but due to the smaller offset they may not supersede 1 kHz as strongest component.
- **Orange**: 3-4 kHz components rise slower than 2 kHz and are generally quieter than 1 kHz, but are probably more present than the components at 2 kHz for lower speeds.
- **Red**: Components over 4 kHz have a small intercept, so they will generally be quieter and will only have an influence at higher speeds.
- **Light blue**: 500 Hz components rise slower than 1 kHz but due to a similar intercept with similar values for (very) low speeds.
- **Dark blue**: Not all measurements provided reliable values for frequencies below 250 Hz. The ones that are shown in the graph are close to the values for higher frequencies and only relevant for higher speeds. Of course the A-weighting is a relevant factor for the small intercept.

Figure 15 also shows that the analysis of octave bands will give a good overview of the spectral behaviour.

**Octave-band analysis**

The coefficients of determination for the octave-band levels can be found in Table 6, while the corresponding levels are displayed in Figure 16.

**Table 6: Coefficients of Determination R² for the octave band analysis**

<table>
<thead>
<tr>
<th></th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre A</td>
<td>0.938</td>
<td>0.968</td>
<td>0.964</td>
<td>0.987</td>
<td>0.994</td>
<td>0.995</td>
<td>0.994</td>
</tr>
<tr>
<td>Tyre B</td>
<td>0.980</td>
<td>0.957</td>
<td>0.956</td>
<td>0.989</td>
<td>0.996</td>
<td>0.985</td>
<td>0.984</td>
</tr>
<tr>
<td>Tyre C</td>
<td>0.986</td>
<td>0.978</td>
<td>0.985</td>
<td>0.996</td>
<td>0.992</td>
<td>0.994</td>
<td>0.986</td>
</tr>
<tr>
<td>Tyre D</td>
<td>0.988</td>
<td>0.975</td>
<td>0.981</td>
<td>0.992</td>
<td>0.996</td>
<td>0.998</td>
<td>0.981</td>
</tr>
<tr>
<td>Tyre E</td>
<td>0.964</td>
<td>0.952</td>
<td>0.977</td>
<td>0.983</td>
<td>0.990</td>
<td>0.982</td>
<td>0.993</td>
</tr>
<tr>
<td>Tyre F</td>
<td>0.979</td>
<td>0.979</td>
<td>0.983</td>
<td>0.989</td>
<td>0.996</td>
<td>0.995</td>
<td>0.964</td>
</tr>
<tr>
<td>Tyre G</td>
<td>0.980</td>
<td>0.989</td>
<td>0.985</td>
<td>0.995</td>
<td>0.995</td>
<td>0.991</td>
<td>0.987</td>
</tr>
<tr>
<td>Tyre H</td>
<td>0.992</td>
<td>0.974</td>
<td>0.994</td>
<td>0.989</td>
<td>0.990</td>
<td>0.983</td>
<td>0.986</td>
</tr>
</tbody>
</table>
Figure 16: Sound Pressure Level in octave bands for tyres A to H after the logarithmic regression. The symbols mark the values of the individual measurements.

The level of an octave band for the regression is taken at the point in time at the maximum of the overall level. For the 125 Hz and 250 Hz octave band we used a polynomial of order two to fit to the logarithmic speed. This improved the correlation. In this analysis for every octave band the 3 dB criterion was checked manually, so there are different numbers of data points available for each octave band. The extrapolated segments in the figure are again marked by dotted lines. Especially with the second order polynomial one must be very careful with the extrapolated data (for example the 125 Hz band of tyre F).
The correlation works reasonable enough down to 125 Hz. The figure shows the high slope of the 2 kHz band for all tyres. A general shift to higher frequencies is recognizable. For nearly all tyres the 2 kHz and 500 Hz band and the 4 kHz and 250 Hz band change the order respectively for the higher frequency band at higher speeds. Figure 16 also gives a good opportunity to compare the patterns in Figure 15. A more detailed analysis will be presented in the case studies in section 3.3.

**Quarter-tone spectra**

A spectrum is the best way to show the spectral distribution, in comparison with the overall level the contribution of spectral components is recognizable. Figure 17 to Figure 20 show the spectrum for different speeds derived from the moving average filter of the quarter tone analysis together with the overall level derived from the regression analysis of the broadband signal. If the coefficient of determination is lower than 0.9 the frequency band is dotted. This happens more in the lower frequency region, because of a lower signal-to-noise ratio. The following graphs (Figure 17 to Figure 20) have the same span of 35 dB of the L_{AFmax} for the spectrum and 7 dB for the overall level for better comparison. Spectra for tyres with extrapolated data at this speed are not considered. Based on the number of available measurement results, the following speeds have been chosen: 30, 55, 80 and 110 km/h.

**Detailed analysis for 30 km/h** (Figure 17): This speed is representing the lower speed range. All tyres show a significant peak at 250 Hz beside the main peak at around 1 kHz (even if tyre I was measured on a different test site with a different surrounding). If we take the 8.6 dB damping of the A-weighting into account the peak is nearly as strong as the main peak. The tyres show a varying distribution. The main peak for tyres A to H is somewhere between 930 and 980 Hz. The peak of tyre I is at 1100 Hz. Tyre A is the loudest tyre at this speed and shows a very distinct peak at 3200 Hz in comparison to the other tyres. At about 550 Hz another peak can be found for the tyres C to F. The maximum difference between the strongest and lowest tyre in a frequency band spans about 10 dB at 2 kHz and also the order of the tyre changes over frequency, except tyre A is the loudest tyre for nearly the whole frequency range. Tyre H is the only tyre with a distinct extra peak (2 kHz).

![Figure 17: Spectrum (left) and overall level (right) of all tyres at 30 km/h.](image-url)
Detailed analysis for 55 km/h (Figure 18): This speed represents the average value between 30 km/h and 80 km/h. At 55 km/h the differences between the tyres are less obvious also the difference between loudest and quietest tyre in a frequency band is reduced to about 7-8 dB. Also the overall spectrum is smoother. Nevertheless the frequency of the most distinct peaks stay the same, so they are not speed related. The peak at 550 Hz is hardly recognizable any more, also the peaks at 250 Hz and 3.2 kHz are widened. At this speed the overall level difference is the smallest which is also the case for the main peak at around 1 kHz.

**Figure 18: Spectrum (left) and overall level (right) of all tyres at 55 km/h.**

**Detailed analysis for 80 km/h** (Figure 19): In the common standards (ISO 11819-1, 2002) and (UN Reg.117, 2014) the measurements are normalized to 80 km/h so the performance at this speed from the regression is rather important. The samples are very close together. The difference goes down to 6 dB in the frequency bands. The peaks at 250 Hz and 3 kHz are again widened, but at 2 kHz also the other tyres beside tyre H start to show a significant higher level in comparison to adjacent frequencies. Also it is recognizable that frequencies above 1 kHz up to 4 kHz rise stronger with higher speeds than frequencies below 1 kHz as predicted from the regression coefficients. Tyre B is very dominant from 1 to 2 kHz which yields in a higher overall level. Tyre I has a stronger main peak than tyre A, but is significant lower at other frequencies with lower levels and has a significant lower overall level. So the level of the main peak doesn’t necessarily determine the overall level even though the other frequency components are more than 8 dB lower.
Figure 19: Spectrum (left) and overall level (right) of all tyres at 80 km/h.

**Detailed analysis for 110 km/h** (Figure 20): This speed is representing the upper speed range. For lower frequencies there is no other peak beside the main peak visible. Another prediction from the regression analysis is confirmed that 2 kHz rise stronger then 3-4 kHz. Tyre B shows a widened main peak. Tyre H has the strongest peak at about 2 kHz, which is nearly as high as its peak at 1 kHz. But with low levels at low frequencies the tyre is still the quietest. Tyre A is now amongst the other tyres, but with its higher main peak is still the second loudest tyre.

Figure 20: Spectrum (left) and overall level (right) of all tyres at 110 km/h.
3.3 Case studies

In the following case studies we focus on four tyres which were very distinctive in the analysis presented in section 3.2, namely tyre A, B, D and H. After a short description and properties of the tyres the spectral behaviour in regard to different speeds is discussed. The octave regressions are presented followed by the spectrum of the tyre at different speeds. The coefficient of determination is higher than 0.9 for the octave band and overall analysis, extrapolated data is marked with a dotted line. In the spectra the components with a coefficient of determination below 0.9 are marked with dotted lines and spectra at speeds with extrapolated data are omitted. The spectra are again derived from the regression analysis of the smoothed quarter tone analysis (1/6-octave).

3.3.1 Dunlop Sport BluResponse (Tyre A)

The first case study deals with the tyre Dunlop Sport BluResponse and its measurement results. The tyre uses a polymer compound to give a better grip and handling on wet roads.

**Dunlop Sport BluResponse**

- Brand: Dunlop
- Line: Sport BluResponse
- Dimensions: 205/55 R16 91H
- Rolling resistance: B
- Wet grip: A
- Noise Emission: 68 dB

The overall level in Figure 21 is mainly influenced by the octave components at 1 kHz. The order of the second and third component (500 Hz and 2 kHz) and the fourth and fifth component (250 Hz and 4 kHz) change for high speeds so the respective higher frequency component is more dominant for high speeds. This transition happens at 50 and 60 km/h.

![Figure 21: Overall and octave band level regression over speed.](image)
In the spectrum in Figure 22 one can see that this strong rise is limited to the frequency range 1 to 4 kHz. The peaks in the spectrum nearly stay the same in their width and position. Even though the coefficient of determination is for lower speeds below 0.9 the spectrum looks plausible.

![Figure 22: Spectrum (left) and overall level (right) for different speeds of tyre A.](image)

### 3.3.2 Goodyear Efficient Grip (Tyre B)

The Goodyear Efficient Grip is the standard equipped tyre for the Renault Fluence Z.E.. A lightweight structure with an advanced tread compound shall reduce the rolling resistance. Also a special block design is used for a lower noise. In our measurements the tyre was amongst the loudest.

**Goodyear Efficient Grip**

- Brand: Goodyear
- Line: Efficient Grip
- Dimensions: 205/55 R16 91H
- Rolling resistance: C
- Wet grip: C
- Noise Emission: 68 dB

In Figure 23 the main level is mostly influenced by the octave band of 1 kHz. At very high speeds also 2 kHz show an effect. There aren’t any measurement points to analyse the behaviour below 40 km/h. The dotted lines in Figure 23 should be considered with care. Above 40 km/h 2 kHz is the second strongest component. Also 4 kHz show a strong rise from the fifth strongest octave band to nearly the third. The spectrum in Figure 24 shows a very bad correlation of the measurements for low speeds. The slope for higher frequencies above 1 kHz is nearly linear and not dependent on speed. So there aren’t extra peaks in this range.
3.3.3 Pirelli Cinturato P1 Verde (Tyre D)

The Pirelli Cinturato P1 Verde has significant worse labels than the Goodyear Efficient Grip. Nevertheless it performed quite well in our measurements. The tyre uses an optimized tread design with specific pitch sequences and hybrid materials.

1 kHz has the main contribution to the overall level in Figure 25, the influence of other frequency bands decreases with higher speeds. 500 Hz and 2 kHz are mostly about the same level, whereas the contribution of 250 Hz decreases. 4 kHz is constantly quieter than 2 kHz over speed. The spectrum in Figure 26 is the most symmetric spectrum of all samples and only at about 1 kHz and 3.4 kHz peaks are visible. Also the measurement conditions were very good, so even for 125 Hz the correlation is reliable.
Pirelli Cinturato P1 Verde

- Brand: Pirelli
- Line: Cinturato P1 Verde
- Dimensions: 205/55 R16 91H
- Rolling resistance: B
- Wet grip: B
- Noise Emission: 70 dB

Figure 25: Overall and octave band level regression over speed.

Figure 26: Spectrum (left) and overall level (right) for different speeds of tyre D.
3.3.4 Hankook Kinergy Eco (Tyre H)

The Kinergy Eco achieves high fuel efficiency through the use of a vibration control technology. Nano-scale silica particles are used in the compound, in order to optimize grip and at the same time reduce rolling resistance. The Hankook Kinergy Eco is one of the quietest tyres in the test.

**Hankook Kinergy Eco**
- Brand: Hankook
- Line: Kinergy Eco K425
- Dimensions: 205/55 R16 91H
- Rolling resistance: B
- Wet grip: B
- Noise Emission: 70 dB

The most distinct aspect of this tyre is the more or less even distribution of the energy between 1 and 2 kHz. So the overall level is dependent on both components, see Figure 27. The percentage of 2 kHz increases very strongly with speed. The 500 Hz component is close to the 4 kHz component in level. 250 Hz is relatively decreasing to its stronger components. This is due to a peak in this frequency band for lower speeds which is clearly visible in Figure 28. Also the two peaks just below 1 and 2 kHz are clearly visible.

![Figure 27: Overall and octave band level regression over speed.](http://www.oeamtc.at/)
**Figure 28: Spectrum (left) and overall level (right) for different speeds of tyre H.**

### 3.4 Summary of pass-by measurement results

The sound pressure level of a passing-by car is very dependent on speed, especially for an electric vehicle or hybrid vehicle in electric mode. From 20 to 130 km/h the sound pressure levels change about 30 dB, which equals a factor of 1000 for the energy. But the quietest tyre at low speed must not be the quietest tyre at high speed. At low speeds (20 km/h) tyre A is louder than the rest, closely followed by tyre B and then a group of tyres E, F, G and H, which are in middle. C, D and I are to be considered the quietest tyres for low speeds. Tyre I was especially dedicated for EV and is particularly quiet in some frequency areas. At high speeds (120 km/h) tyre A and B are again the loudest tyres, whereas tyres C to G are very close in the middle. Tyre H is the quietest tyre at high speeds. The maximum spread between two investigated tyres never exceeds 3.6 dB for lower speeds (20 - 50 km/h) and for speeds between 50 and 120 km/h the spread never exceeds 2.4 dB.

General similarities in the spectral behaviour could be found in the sample, for example the higher slope of 2 kHz and lower slope of 500 Hz components to speed in comparison to the most dominant 1 kHz band. So the sample showed not only a changing spectral distribution over speed but also a common behaviour. The spectra at different speeds give a comparison of occurring peaks and showed the dominance of the 1 kHz octave band. It is interesting to note, that in some cases the ascending order of the tyre levels at 1 kHz octave band is different from the ascending order of the overall levels. Especially for frequencies below 1 kHz the differences in the spectral distribution are less significant.

The case studies showed the differences between the tyres. Spectral components can rise differently with speeds so the relative difference of the distribution changes. The Dunlop BlueResponse and Hankook Kinergy Eco have a very distinct peak at 1 kHz. The Pirelli Cinturato P1 Verde and the Goodyear Efficient Grip have a broader peak and an overall smoother spectrum. The Hankook Kinergy Eco is special among all tyres because its main level is dependent on two octave bands (1 and 2 kHz). But the energy in both bands is significant smaller than for the other tyres so even though the spectrum is broader, the overall energy is less.
4 Rolling noise with regard to EU noise labels

4.1 Comparison of the measurement results with the EU noise labels

EU noise labels, used for tyre marking, are determined by the tyre manufacturers (or their representative) for type approval according to the procedure described in the UN (ECE) regulation No. 117. The measurement conditions and method for light vehicle tyres include the following specifications:

- The road surface shall be in accordance with ISO 10844:2011. The test site shall offer semi-free field conditions.
- The vehicle is fitted with four identical tyres.
- The A-weighted maximum sound pressure level (time weighting F) is recorded at vehicle coast-by (engine off, gear at neutral) on microphones located 7.5 m from the track centre line and 1.2 m above the ground.
- Temperature corrections are applied, according to the test surface temperature, to normalize to the reference 20°C.
- A minimum of eight measurements on each vehicle side is required, with test speeds ranging from 70 to 90 km/h.
- A regression equation relating the maximum noise level to log(speed) is determined, and the noise level at the reference speed 80 km/h is inferred.
- The final result is reduced by 1 dB(A) to take account of measuring inaccuracies and rounded down to the nearest whole value.

The EU noise labels of the 8 tyres fitted to the Fluence and the specific tyre fitted to the ZOE, listed in Table 4, are compared with the noise levels measured on the AC11 road surface, calculated from the regression equations provided in Table 5 at the reference speed 80 km/h (Figure 29).

![Figure 29](image)

Figure 29: Noise levels measured at 80 km/h on AC11 compared with the EU noise labels, for the 8 tyre types fitted to the Fluence (blue) and 1 tyre fitted to the ZOE (red).
The noise measurements at 80 km/h are spread on a reduced noise scale in relation to the EU labels: the tyre labels range over 4 label values from 67 to 70 dB(A)) while the measured noise levels are contained within an interval width of approx. 2 dB(A). Furthermore, it turns out that the EU labels do not properly render the tyre ranking given by the noise measurement on the AC11 surface: the tyre with the lowest label and those with the highest labels yield similar noise levels, whereas the largest noise levels are due to tyres with an intermediate label.

The lack of a common trend can be noticed between noise labels and the actual noise levels. A possible cause is that the ISO surface used for the EU noise label is a smooth surface, which doesn’t excite many vibrations on a tyre. This may also explain why the mean of the EU Noise Label is lower.

Other recent studies pointed out a similar behaviour, underlying a lack of representativity of the exterior noise EU-labels with actual noise levels on operational road surfaces, for instance (Kragh, 2013) which reports a study involving 31 different tyres tested on Nordic road surfaces and (Świeczko-Zurek, 2014) where 12 tyres were tested either on a drum with road replicas or by the CPX method on road surfaces. The adequacy of the ISO surface for inferring tyre ranking on actual roads is questioned.

Also there is no evidence of any trend between fuel efficiency or wet grip labels and actual noise levels at 80 km/h.

4.2 Investigating the concept of 'low-noise' tyres

The concept of low-noise tyres has not yet been clearly defined, as underlined in (Berge, 2012). It can be stated as referring to tyres granted with a noise label either 1 dB or 2 dB under the type approval limit value, or even 3 dB lower than the limit value which corresponds to a noise rating with a 1-wave pictogram. The impact of one or the other definition of a low-noise tyre within the tyre set previously measured is analysed.

All the 9 tyres investigated (Fluence and ZOE) belong to the same tyre subclass C1b featured with a nominal section width of 185 to 215 mm and a limit value of 71 dB(A). From Table 4 it may be easily checked that all tyres comply with this rolling noise limit value.

If the low-noise tyre definition would be “at least 1 dB below the noise limit value”, i.e. an exterior noise label not greater than 70 dB(A), then no tyre should be removed from the tyre set since they all meet this definition. The mean noise level at 80 km/h, computed from the regression equations, is 74.0 dB(A).

If the low-noise tyre definition would be “at least 2 dB below the noise limit value”, i.e. an exterior noise label not greater than 69 dB(A), then five tyres should be disregarded since only four tyres (A, B, C, F) fulfil this definition. Two of the remaining tyres are among the loudest tyres measured; another is in the middle range while the fourth is one of the quietest tyres of the collection (Figure 31). Then, if these were the only tyres fitted to passing-by vehicles with an even distribution, the emitted noise would be slightly increased (the rolling noise average at 80 km/h increases by 0.6 dB(A)).
Figure 30: Noise levels measured at pass-by with 8 tyres on the Fluence and 1 tyre on the ZOE – the red surface includes all the dots related to the Fluence tyres.

Figure 31: Noise levels measured at pass-by with the 4 tyres meeting the low-noise definition “2 dB below the limit value” – the red surface includes all the dots related to the 8 Fluence tyres.
Finally, if the low-noise tyre definition would be “at least 3 dB below the noise limit value”\(^1\), i.e. an exterior noise label not greater than 68 dB(A), then yet another tyre would be removed from the collection. Only three tyres (A, B, C) are still selected: the two noisiest over the most speed range and one of the quietest tyres measured with the Fluence on an AC11 road surface. Thus, the resulting average noise level at 80 km/h eventually increases by 0.7 dB(A) when compared to the whole tyre collection.

![Diagram showing noise levels vs speed for different tyre types.](image)

**Figure 32**: Noise levels measured at pass-by with the 3 tyres meeting the low-noise definition “3 dB below the limit value” – the red surface includes all the dots related to the 8 Fluence tyres.

The lack of connection between the noise labels and the actual noise values measured during the vehicle pass-by tests, already underlined in section 4.1.1, would paradoxically lead to a slight (if not insignificant) worsening of the emitted noise if choosing more stringent tyre noise criteria based on the standard tyre labels.

\(^1\) This definition is used for instance by the European Tyre & Rubber manufacturers’ association (www.etrma.org).
4.3 Are EV-specific tyres quiet?

Within the tyre collection used for the measurement, two tyres may be more particularly emphasized with regard to electric vehicles:

- the Goodyear EfficientGrip which, though also available on the market for any vehicle, has been selected by the car manufacturer to exclusively fit the Fluence Z.E.
- the Michelin Energy E-V which has been specifically designed for the ZOE.

When comparing the results specific to the two “EV tyres” with the overall noise range of the 9 tyre measurements (Figure 33), it turns out that one of them belongs to the loudest tyres whereas the other is among the quietest tyres of the collection over the measurement speed range. Thus it can be inferred that, as far as rolling noise is the dominant source, a fleet of electric vehicles fitted with such tyres would not lead to a different global noise level than with common tyres. This is also true in the octave bands higher than 1000 Hz, whereas the Michelin Energy E-V fitted on the ZOE may significantly reduce the noise contribution in the octaves below 500 Hz. It may be recalled that these two tyres have been measured with different vehicles on different test sites with similar types of road surface: the result discrepancies cannot be definitely attributed to the sole tyre contribution and road texture differences might be suspected as well.

![Figure 33: Noise levels measured at pass-by with the 2 tyres specifically selected to be fitted on EVs (measurements and regression lines) – the red surface includes all the dots related to the 8 Fluence tyres.](image)

A quite similar behaviour was pointed out in a study carried out by Ejsmont et al., where 2 tyres specially designed for EVs and HEVs and 15 classic tyres have been investigated (Ejsmont, 2014). The authors concluded that “tires specially designed for Low Emission Vehicles are not particularly quiet. At best they emit tire/road noise of “average” level.”
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5 Rolling noise of EVs and CNOSSOS-EU

CNOSSOS-EU is the European method proposed for environmental noise prediction (Kephalopoulos, 2012). The prediction of traffic noise relies on a vehicle noise emission model, composed of a propulsion noise component and a rolling noise component, specified by vehicle category in octave bands. Details on CNOSSOS-EU model for vehicles are available in the final report of WP2 (Pallas et al., 2014). Whereas Work Package 2 focused on the noise emission of electric vehicles to derive correction terms to be applied to the propulsion noise component of CNOSSOS-EU, the present section will compare the pass-by noise measurements with CNOSSOS prediction model to consider the relevance of corrections for the rolling noise component.

It will rely on the measurements performed by AIT with eight different tyres and the Fluence Z.E on one test site, and on the measurements carried out by IFSTTAR with five light vehicles running in electric mode on a second test site with a different road surface. Results on global levels and in octave bands will be investigated.

5.1 AIT measurement results

The measurements with the FLUENCE Z.E. and eight different sets of tyres took place on a site with an AC11 road surface. Only the noise pressure levels with a difference to background noise larger than 3 dB(A) are considered here, either in global levels or in octave bands. No correction, except for the temperature, was applied. The set of measured noise values is represented by a red surface including all noise levels measured at all speeds and for the eight tyres.

A prediction model deriving from CNOSSOS-EU is plotted with the following characteristics:

- The propulsion noise component is the model specified in WP2 for predicting the propulsion noise from electric vehicles.
- The rolling noise component is the one given by the CNOSSOS-EU method for conventional vehicles. Since the AIT measurement road surface corresponds to the CNOSSOS reference conditions, no road correction term is added.

In the following, only the rolling noise and the total noise of the model are plotted. Since CNOSSOS-EU is an average model intended to represent an average vehicle on an average road surface whereas the sample dispersion may be significant, we will consider the model as satisfactory if the total noise is not disjoint from the red surface over most of the speed range. Figure 34 refers to the global levels and points out that the model overestimates only slightly the collection of global values measured on this test site. Figure 35 allows us to investigate more precisely in frequency:

- The octave 63 Hz is disregarded and uncommented, since the model is totally inappropriate. This results largely from the propulsion noise component, for which reservations had already been made in WP2.
- In the octave 125 Hz and 250 Hz, the rolling noise component seems underestimated by 2-3 dB(A), particularly noticeable at high speed.
- The model is satisfactory in the octaves 500 Hz, 1000 Hz, 4000 Hz and 8000 Hz.
- The rolling noise component is clearly overestimated by 2-3 dB(A) in the octave 2000 Hz, with a significant contribution to global levels.
Figure 34: Global noise levels at 7.5 m measured with the 8 tyres on AC11 (red surface) – dashed line: rolling noise model given by CNOSSOS-EU – continuous line: total noise model for EVs.

Figure 35: Noise levels in octave bands at 7.5 m measured with the 8 tyres on AC11 (red surface) – dashed line: rolling noise model given by CNOSSOS-EU in reference conditions – solid line: total noise model for EVs.
5.2 **IFSTTAR measurement results**

The measurements involved five light vehicles of different sizes running in electric mode, involving various tyre sizes and makes/models. The test site had a DAC 0/10 road surface. Only the noise pressure levels with a difference to background noise larger than 3 dB(A) in global levels and larger than 5 dB(A) in octave bands have been considered. A correction term was applied when this difference was lower than 10 dB(A). This processing is detailed in the WP2 final report. The set of noise values measured at 7.5 m is represented by a green surface including all the regression curves describing the noise emission of the five vehicles in electric mode.

A prediction model deriving from CNOSSOS-EU is plotted with the following characteristics:

- The propulsion noise component is the model specified in WP2 for predicting the propulsion noise from electric vehicles.
- The rolling noise component derives from the CNOSSOS-EU method for conventional vehicles, but a correction term has been included to take account of the actual road surface which differs from the CNOSSOS reference conditions. CNOSSOS-EU recommends applying a spectral correction factor on rolling noise for dense surfaces which differ from the reference conditions. This correction factor is given by:

\[
\Delta L_{WR,i}(v) = \alpha_i + \beta \log\left(\frac{v}{v_{ref}}\right)
\]

where \(\alpha_i\) is the correction in the octave band \(i\) at the reference speed \(v_{ref}\) and \(\beta\) is the speed effect on rolling noise reduction (assumed independent of frequency). In the present case, which involves a common French road surface, the correction terms have been determined by using the data available in DEUFRABASE\(^2\). This database makes average third-octave rolling noise spectra of various road surfaces existing in France and Germany freely available. From the spectra given for an SMA 11 surface (considered here as being in accordance with CNOSSOS-EU reference road surface) and for a BBSG 0/10 surface (corresponding to the actual road surface type DAC 0/10 of IFSTTAR measurement\(^3\)), the correction terms \(\alpha_i\) given in **Table 7** have been determined. No correction term is available in the octaves 63 Hz and 8000 Hz. Then the corrected model for global levels is calculated over the octaves 125 Hz to 4000 Hz, which is in accordance with the CNOSSOS validity domain. DEUFRABASE does not provide any information on the speed index of the road surfaces. By reference to the French method NMPB08, the two road surfaces belong to the same road surface category (Hamet, 2010)). Then, the coefficient \(\beta\) has been taken as \(\beta = 0\).

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\(^2\) DEUFRABASE website: [http://deufrako.bast.de/](http://deufrako.bast.de/)

\(^3\) This road surface is equally named DAC 0/10 or BBSG 0/10 in the text and figures.
Table 7: Correction terms applied to the CNOSSOS-EU rolling noise component for the DAC 0/10 road surface.

<table>
<thead>
<tr>
<th>Octave $i$</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction term $a_i$ (dB(A))</td>
<td>-0.74</td>
<td>-0.83</td>
<td>-1.91</td>
<td>-2.91</td>
<td>-2.91</td>
<td>-2.19</td>
</tr>
</tbody>
</table>

Figure 36 refers to the global levels and shows that the corrected model fits satisfactorily to the collection of global values measured on this test site. Figure 37 allows us to investigate more precisely in frequency:

- The measurement in the octaves 63 Hz and 8000 Hz are plotted for information only. No model is available in these frequency bands.
- Except for the octave 125 Hz where the results at high speeds might require a slightly higher rolling noise contribution, the model is quite satisfactory in all the other octaves, particularly at high speeds where the rolling noise contribution is dominating.

Figure 36: Global noise levels at 7.5 m measured with the 5 vehicles in electric mode on DAC 0/10 (green surface) – dashed line: rolling noise model corrected for the road surface – solid line: total noise model for EVs.
Figure 37: Noise levels in octave bands at 7.5 m measured with the 5 vehicles in electric mode on DAC 0/10 (green surface) – dashed line: rolling noise model corrected for the road surface – solid line: total noise model for EVs.
5.3 Conclusions and recommendations for CNOSSOS-EU for EVs

Taking account of the following findings on tyres and electric vehicles:

- The selection of tyres for electric vehicles by car and tyre manufacturers is firstly driven by fuel efficiency requirements, relying on the rolling resistance performance of the tyre. Consideration of rolling noise is of secondary importance.
- There is no evidence of a trend between the rolling resistance performance and the rolling noise measured on actual road surfaces.
- The few tyres selected by car manufacturers to be fitted on their electric vehicles and tested to date do not acoustically behave differenty from conventional tyres.
- Any tyre selection relying on a low-noise requirement based on EU noise labels would have no obvious effect on the rolling noise measured on actual road surfaces.

as well as the following findings based on the joint observation at high speeds of the measurement results and of the CNOSSOS-EU model corrected for the EV propulsion noise according to WP2 results and without any modification of the rolling noise component (except for a correction linked with the road surface type):

- the model depicts the IFSTTAR measures quite well.
- the model depicts the AIT measures quite well in global levels, but with more or less significant discrepancies according to the octave bands.

it may be inferred, from the present perspective, that no correction is required for the rolling noise component given in CNOSSOS-EU.

To sum up, we would recommend for the model CNOSSOS-EV (standing for an EV extension of standard CNOSSOS-EU):

- to exclude the octaves 63 and 8000 Hz from the model specifications due to the lack of reliable information (in accordance with the CNOSSOS-EU validity domain for the other vehicles),
- to apply the correction terms of the propulsion noise already proposed in WP2,
- to use ‘as is’ the rolling noise component given by CNOSSOS-EU for conventional vehicles.

Due to the still limited amount of data available for assessing the proposed model, further investigation is required and any laboratory or organism having appropriate data is welcome to compare its own measures with this CNOSSOS-EV model in order to further the model validation.
6 Task 3.4: EV level-correction factor

Task 3.4 was originally part of Work Package 3, aiming at modelling tyre-road emission for electrical vehicles. After the findings of the other WP3 tasks, this goal loses its usefulness within this Work Package. For this reason the task has been slightly modified and will take care of the Electrical Vehicles (EV) level correction factors. As this issue becomes a more qualitative than quantitative nature, this task was moved to Work Package 4, which is dealing with the estimation of the potential noise impacts of electric vehicles.
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7 Summary and conclusions

The present document is the final report of Work Package 3 of the FOREVER project. The aim of this Work Package was to investigate potential and dedicated tyres currently used for electric vehicles and their noise output. The following activities have been performed and the following conclusions can be drawn:

- A tyre selection has been performed in order to represent the current market of tyres for electric and hybrid vehicles. As shown by the literature study carried out within task 3.1, the selection of tyres for electric vehicles by car and tyre manufacturers is currently driven by fuel efficiency requirements, relying on the rolling resistance performance of the tyre. No relation is currently present between rolling resistance and rolling noise. There is currently no evidence of a trend between the rolling resistance performance and the EU rolling noise labels.

- Using the selected tyres controlled pass-by measurements according to ISO 11819-1 have been performed, and the results have been analysed. As expected from the literature review the relation between the overall maximum pass-by noise in dB(A) and the logarithmic vehicle speed is linear, where the maximum contribution to overall noise is evidently coming from the rolling noise. The maximum spread between two investigated tyres never exceeds 3.6 dB for lower speeds (20 - 50km/h) and for speeds between 50 and 120 km/h the spread never exceeds 2.4 dB.

- General similarities in the spectral behaviour could be found in the sample of tyres, for example the higher slope of 2 kHz and lower slope of 500 Hz components to speed in comparison to the most dominant 1 kHz band. So the sample showed not only a changing spectral distribution over speed but also a common behaviour. The spectra at different speeds give a comparison of occurring peaks and showed the dominance of the 1 kHz octave band.

- The case studies analysed the differences between the selected tyres in detail. Spectral components can rise differently with speed so the relative difference of the distribution changes. Nevertheless these differences have only little relevance on the overall levels.

- Investigations conducted on noise measurements at pass-by of two electric vehicles successively fitted with nine different tyre sets (eight sets on the first vehicle and one set on the second vehicle) did not bring to light any relation between the exterior noise EU-label and the noise on actual road surfaces, in particular regarding tyre ranking. This has impacts on the concept of low-noise tyres since a possible requirement on the limit value based on the EU-label would not lead to select the quietest tyres on actual dense road surfaces and would probably not modify the road traffic noise.

Based on these conclusions from the WP3 investigations, then the following are considered to be the key outcomes:

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4 There is little that can be done about this. Tyre noise depends on a number of factors including the tyre compound, width and tread pattern (and implicitly the age of the tyre), road surface stone size, texture (and implicitly age), vehicle weight, speed and acceleration and surface wetness and weather conditions. Any type approval test on any surface can only account for a small fraction of these factors and will be unlikely to correlate with roadside noise levels in circumstances that differ from the test. This issue has been considered in the past by ISO WG42 with the primary conclusion that the harmonisation of road surfaces across Europe would be an important first step in the right direction and help considerably in defining a quiet tyre.
1. Tyres designed or selected by manufacturers for EVs have no effect on global rolling noise compared to conventional tyres. A wider set of EV specific tyres is required to conclude on frequency differences possibly impacting the roadside traffic noise.

2. On the basis of current knowledge, it turns out that rolling noise from light electric vehicles does not differ from conventional vehicles. Thus, for predictions of traffic noise according to the European assessment method, the use of the rolling noise component given in CNOSSOS-EU remains available without amendment for light electric vehicles. Only the propulsion noise component requires correction terms, as proposed in the final report of Work Package 2 of the FOREVER project.
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