LIFE E-VIA

"Electric Vehicle noIse control by Assessment and optimisation of tyre/road interaction"

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Abbreviations:

AF	Alternative Fuel
AVAS	Acoustic Vehicle Alerting System
BEV	Battery Electric Vehicle
CNOSSOS-EU	European Common Noise Assessment Methods
CPB	Controlled Pass-By
DAC	Dense Asphalt Concrete
DPAC	Double-layer Porous Asphalt Concrete
EEA	European Environment Agency
ELCV	Electric Light Commercial Vehicle
END	Environmental Noise Directive
EV	Electric vehicle
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
HVAC	Heat, Ventilation and Air-Conditioning
ICEV	Internal Combustion Engine Vehicle
LCV	Light Commercial Vehicle
NMAS	Nominal Maximum Aggregate Size
OEM	Original Equipment Manufacturer
PERS	Poro-Elastic Road Surface
PHEV	Plug-in Hybrid Electric Vehicle
PWM	Pulse Width Modulation
REEV	Range-Extended Electric Vehicle
SD	Surface Dressing
SMA	Stone Mastic Asphalt
SPB	Statistical Pass-By
SPL	Sound Pressure Level
WHO	World Health Organization
WOT	Wide Open Throttle
ZEV	Zero-emission Vehicle

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Executive Summary

The project LIFE E-VIA aims to tackle noise pollution from road traffic noise, in a future perspective involving a consistent portion of electric and hybrid vehicles. By combining knowledge of road optimization and tyre development, it will test an optimized solution for reducing noise in urban areas and Life Cycle Cost with respect to actual best practices.

The project includes three preparatory actions, consisting of state-of-the-art studies on the components implicated in the issue: the electric vehicles (EVs), the quiet pavement technologies and the tyre role in the context of EVs vs. conventional vehicles.

Action A1 provides an overview of the concern of electric vehicles and of their noise emission. It intends to highlight the key aspects to be taken into consideration in order to achieve the most effective and relevant implementation work, in the light of the latest technical and scientific knowledge. In the shift from conventional mobility to electromobility, the present study deals with: the electric vehicle fleet characteristics, the changed driving behaviours induced by the vehicle specificities, the different noise source features with a sharp focus on rolling noise, the changes in the noise perception by the citizens and the consideration of electric vehicles in the noise prediction methods.

The electric and hybrid vehicle fleet is developing fast in Europe and in many countries in the world. The dynamism of the electric vehicle market is reflected both in terms of technological innovations and in the increase in the number of vehicle models available by manufacturers. In the European area, about 1.4 million of light vehicles were in circulation at the end of 2019, with a market share of new registrations of EVs reaching 3% in 2019. This European market is by far dominated by battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) of the passenger car category, which is expected to stay the dominant market in the next years. The international outlook for EV fleet is estimated to reach between 15% and 30% of the global vehicle fleet by 2030. Consequently, this substantiates the LIFE E-VIA project’s focus on this vehicle category within the implementation actions. In particular, the current BEV models dominating the total fleet in the European area help in orienting the selection of BEVs for acoustics tests planned in the tyre-pavement coupling study on Université Gustave Eiffel reference test track in Nantes (France) within action B2. Therefore, it is recommended to consider at least one model per segment in category M1 (i.e. Renault Zoe and/or BMW i3 in segment B, Nissan Leaf and/or VW e-Golf in segment C and Tesla Model 3 in segment D). An additional model shall be considered in the commercial vehicle category N1, i.e. Renault Kangoo ZE.

Electric vehicles have several technical features that differ from conventional vehicles and infer changes in the driving behaviour, namely the limited vehicle range, the availability of regenerative braking and a set of different sensations (acceleration, torque, acoustical perception) arising when driving EVs. After becoming experienced, EV drivers show anticipation, use deceleration to efficiently benefit from the regenerative braking and try to drive economically by favouring a constant speed as far as possible, with the aim of effectively managing the limited vehicle range. They also have a perception of the vehicle, either from technical performance (acceleration ability and torque availability) or from acoustical feedback, which differs from conventional vehicles. This may affect their driving behaviour in different ways, often by driving more smoothly with effects on speed, acceleration/deceleration rates and lengths, but also sometimes by more aggressive driving schemes noticed with fleet users or users having powerful EVs. The ongoing traffic conditions and vehicle range certainly play a central role in the adoption of one or the other attitude. Smooth driving is favourable to propulsion noise and rolling noise reduction, while aggressive driving leads to noise increase during accelerating and decelerating driving conditions, reducing the quieting impact of EVs on road traffic noise. Therefore, the specificities of driving behaviour shall be considered in the characterisation of tyre/road and vehicle noise emission during the tests on the prototype and on the pilot area (implementation actions B2 and B4). In addition to steady-speed driving conditions, acceleration and deceleration situations shall be performed, thus providing noise emission skills in

relation with the diversified performance of the tested electric vehicles. Deceleration tests should include regenerative braking situations without frictional brakes as far as possible.

Powertrain noise (mainly motor noise), rolling noise and AVAS[1] are main specific noise contributions on EVs. Even if the propulsion noise is lower than on conventional vehicles, the motor noise has a spectrum rich of tones that make it audible, even unpleasant, at least at low speed. Existing studies have found that for an electric vehicle, tyre/road noise exceeds propulsion noise at a speed of 30 km/h and above, sustaining the need of low noise tyres and quiet road surface for noise reduction, including in urban areas. This meets one of the main objectives of the LIFE E-VIA project. However, the literature review points out a lack of information on tyres, pavement types and/or background noise of test sites, leading to some uncertainties in the analysis of vehicle noise emission available from pass-by measurements. Moreover, a main difficulty is the separation of noise sources at low speeds, i.e. propulsion noise and rolling noise, since the driveline turns out not to be the only varying parameter when comparing electric and ICE test vehicles. In addition, accurate noise source evaluation is subject to low background noise. Measurement campaigns planned in action B2 of LIFE E-VIA shall tackle these difficulties in several ways. They will be performed on the reference test track of Université Gustave Eiffel in Nantes (France) which benefits of a relatively low background noise (about 40 dB(A)). Six existing road surfaces with fully characterised properties will be considered for noise measurements (pass-by and close-proximity) of different EV models (sub-action B2.1). A prototype of low noise road surface developed during the project will be built on the same site (sub-action B2.3), then fully characterised from an acoustical point of view and used for tyre optimisation (sub-action B2.4). Regarding separation of noise sources at low speed, pass-by tests will be performed for two Renault Kangoo with strictly identical properties (bodywork and tyres), but with different motor type (i.e. electric or ICE), in order to avoid a bias in rolling noise emission. Additionally, the different EV models will also be measured with a microphone array when rolling on a smooth road surface conforming ISO 10844. This kind of smooth road surface should minimize the rolling noise contribution and will support the separation of noise sources. This methodology will lead to important information regarding rolling noise and optimisation of tyre/road interaction, for optimal mix and tyre developments (actions B1 and B2.4/B7 respectively).

Nowadays, the number of electric vehicles is increasing, involving positive effects, compared to Internal Engine Combustion Vehicles, such as the reduction of noise emissions. In order to make vehicles noticeable, possible solutions may provide non-acoustic or acoustic measures addressed to drivers or pedestrians. Thus, it is important to raise people’s awareness of noise pollution and correlated health effects. Therefore, investigations on human response, including soundwalks and interviews, are crucial for a wider perspective. According to FOREVER project’s method, Vie *en.ro.se*’ aim for Sub-Actions B5.1 is to make participants listen to road traffic noise in presence of different typologies of asphalts and different typologies of vehicles (ICEV and EV) and to distribute related questionnaires (Sub-Actions B5.3). Regarding Sub-Action B5.2, people will be asked to be the passengers of an electric “taxi” in the pilot road. As suggested by Head Acoustics experience, an interview will be conducted. Specific questions will focus on the perception of the comfort and acoustical environment while passing on three different typologies of asphalt and on the perception of the noise due to EVs and ICEVs.

Several road traffic noise prediction models have been developed at a national or international scale, but the majority only refer to conventional vehicles and do not mention electric vehicles. Some of them have anticipated a specific category, but do not yet take EVs further into account in the noise prediction, as is the case with the European method CNOSSOS-EU. Studies have been conducted, either to define a methodology for including EVs in the models or for providing exploratory EV noise emission data. Considering the current state of EV market and the limited share of EVs in the overall fleet, these data rely on a low number of vehicles. The methodologies for characterising noise emission of EVs encounter several difficulties, which are pollution of low noise vehicle to background noise in some frequency bands and at low speed, the impossibility to drive EV in neutral

[1] Acoustic Vehicle Alerting System.

preventing coast-by tests and proper extraction of rolling noise. Within LIFE E-VIA project, these difficulties and solutions shall be considered in actions involving low speed measurements in urban context (Actions B2.1, B2.3, B4.2 and B6). Finally, the choice of the acoustical indicator to be used in the analysis of the CPB measurements should also be considered in light of sensitivity to background noise context.

The literature review performed within the preparatory action A1, together with the companion preparatory actions A2 and A3, respectively on “Quiet pavement technologies and their performance over time” and “Tyre role in the new context of EV and ICEV”, provides solid bases and methodological recommendations regarding the implementation of the LIFE E-VIA project, specifically for the optimisation of tyre/road noise reduction in the context of a growing electric vehicle fleet in urban area.

1 Introduction

Exposure data from the European Environment Agency (EEA) demonstrate that more than 100 million EU citizens are affected by high noise levels negatively impacting human health. Traffic noise alone is harmful to the health of almost every third person in the WHO (World Health Organization) European Region. Twenty percent of Europeans are regularly exposed to night sound levels that could significantly damage health, especially in urban areas. As emerged in Noise Europe Conference (April 2017) and in the WHO guidelines published in October 2018, the increased stringency of EU at source standards needs to be balanced against other effective measures such as road surface and/or tyre improvements and urban planning measures as well.

One of the solutions universally recognized as the best to reduce noise in urban areas, from both the point of view of noise and air quality, is the introduction of electric mobility.

Traffic noise mainly consists of powertrain noise and tyre/road noise (i.e. rolling noise). With the progress of modern Internal Combustion Engines (ICE), tyre/road noise dominates after 40 km/h for steady-speed traffic. This threshold is even lower for Electric Vehicles (EVs) with strongly reduced engine noise, thus leading to a higher relative contribution of tyre/road noise to the overall exterior vehicle noise. Similar effects can also be observed for the contribution of the tyre rolling resistance to the vehicle's energy consumption. This affects the emission of CO_2 and air pollutants, and the achievable mileage which is crucial for the public acceptance of EVs. Thus, for the changed requirements of EVs there is a need for in-depth investigations of tyre/road interaction.

A main objective of the project LIFE E-VIA is to reduce noise from roads inside very populated urban areas through the implementation of a mitigation measure aimed at optimizing road surfaces and tyres of EVs.

The present deliverable is the outcome of the preparatory action A1 of LIFE E-VIA. It states current knowledge on light electric vehicle noise emission, including comparisons with Internal Engine Combustion Vehicles (ICEVs) when relevant. It also considers the possible impact of future changes that can be expected on the basis of actual predictions or regulatory evolutions. It mainly consists of a literature survey, considering various aspects affecting either the vehicle or the overall traffic noise emission, focusing on issues of particular interest in order to provide substantiated information for the project's next actions B1-B6.

First, the electric vehicle fleet and its development worldwide and in Europe is considered (section 2). The market share, the distribution in car segments and categories, as well as the expected electric vehicle trends are investigated.

Secondly, the occurrence of changes in the driving behaviour, possibly influencing noise emission and tyre-road contact properties are explored (section 3). More particularly, range anxiety due to the limited vehicle range, the availability and use of regenerative braking, the modified perception of the vehicle and of its performance are considered with regard to driving consequences.

In a third phase, specificities in EV noise sources and noise source emission are examined (section 4), focusing on driveline noise and the electric motor, rolling noise and AVAS (Acoustic Vehicle Alerting System) noise. In particular, outcomes and lessons from several previous international projects involving electric vehicle noise are reviewed.

The next section emphasizes the perceptive dimension of vehicle noise and the changes brought by electrically driven vehicles (section 5). It considers relations to health concerns, annoyance and sound quality and reviews dedicated psychoacoustics metrics.

Finally, the issue of noise prediction is at the core of assessment methods within environmental noise policies. The European method CNOSSOS-EU, like others around the world, involves road vehicle noise models based on conventional vehicles. The opening of noise emission data towards new vehicles like EVs would be a way of producing more realistic assessments of population's exposure to noise, including electromobility (section 6).

Each section summarises at the end the essential findings to enrich the next project implementation actions.

2 Electric vehicle fleet and distribution

2.1 General information on electric vehicles

2.1.1 Vehicle categories

According to [1], the United Nations Economic Commission for Europe (UNECE) has defined vehicle categories for regulatory purposes, enabling manufacturers to benefit from the EU Single Market, and allowing them to export their products beyond the EU. The main categories of vehicles are:

- category M: vehicles carrying passengers;
- category N: vehicles carrying goods;
- category L: 2- and 3-wheel vehicles and quadricycles;
- category T: agricultural and forestry tractors and their trailers.

Vehicles that belong to category M or N are classified as light vehicles (passenger cars and vans) or heavy vehicles (trucks, buses, and coaches). According to European Alternative Fuels Observatory (EAFO [2]), vehicle category M can be sub-classified as follows:

- M1: vehicle used for the carriage of passengers, with no more than eight seats in addition to the driver seat, also known as passenger cars;
- M2: vehicle used for the carriage of passengers, having a maximum mass not exceeding 5 tonnes;
- M3: vehicle used for the carriage of passengers, having a maximum mass exceeding 5 tonnes.

Vehicle category N can be similarly sub-classified as follows:

- N1: vehicle used for the carriage of goods, having a maximum mass not exceeding 3.5 tonnes, also known as Light Commercial Vehicle (LCV) and including pick-up trucks;
- N2: vehicle used for the carriage of goods, having a maximum mass between 3.5 and 12 tonnes;
- N3: vehicle used for the carriage of goods, having a maximum mass exceeding 12 tonnes.

This report will be mainly focussed on the electric vehicles belonging to category M1, i.e. electric passenger cars. Within this category, while not formally regulated, vehicle segments are commonly used based on weight and size characteristics: A (mini cars), B (small cars), C (medium cars), D (large cars), E (executive cars), F (luxury cars), J (Sport Utility Vehicle - SUV, including off-road vehicles), M (multi-purpose cars, including pick-up), S (sports cars).

2.1.2 Technologies of electric vehicles

According to [3], vehicle manufacturers currently propose five main types of electric vehicle technology:

- Battery Electric Vehicles (BEVs);
- Range-Extended Electric Vehicles (REEV), also known as series-hybrid vehicles;
- Hybrid Electric Vehicles (HEVs), also known as parallel-hybrid vehicles;
- Plug-in Hybrid Electric Vehicles (PHEVs);
- Fuel Cell Electric Vehicles (FCEVs).

A BEV is only powered by an electric motor using electricity stored in an on-board battery (most of the time a Lithium-ion battery), which must by regularly charged by plugging in on the local electricity grid. According to [4], BEVs propulsion systems are about 3.6 times more efficient than Internal Combustion Engine Vehicles (ICEVs). Indeed, to move the car a BEV will use about 77% of the total electric energy supplied by the grid (grid - to-wheel calculation [4]), while an ICEV will only use 21.5% of the total fuel energy (tank-to-wheel calculation [5]). Furthermore, the efficiency of the electric motor is often complemented by regenerative braking systems, which help to keep the battery charged during rolling by converting into electricity a part of the energy that would normally be lost as heat during braking. The driving range for current BEV models is typically between 150 km and 500 km.

A hybrid vehicle combines two different sources of energy, i.e. a combustion engine using a fossil or derived fuel and an electric engine. According to [6], there are two main categories of hybridisation:

- Series-hybrid vehicles, corresponding to the above-mentioned REEVs, only working with an electric motor, the ICE having a function of electricity generator powering the electric motor or recharging the battery when it is low;
- Parallel-hybrid vehicles, corresponding to above-mentioned HEVs, working by alternating or associating an ICE and an electric motor that can both drive the car.

If more than two systems are used, one should talk about complex hybrid vehicle. Hybrid vehicles are also designated by micro-hybrid, mild-hybrid or full-hybrid. For micro-hybrid, the electric part of the vehicle is less than 10% of the total power, for mild-hybrid it ranges between 10% and 30% of the total power and for full-hybrid the electric part represents more than 30% of the total power.

In REEVs, the ICE has no direct link to the wheels and the vehicle is solely powered by the electric motor. The combustion engine acts as an electricity generator that permits to increase the driving range of the car by powering the electric motor or recharging the battery during rolling. According to [6], series-hybrid vehicles become interesting in terms of final efficiency when the generator has at least an efficiency of 40%, which is commonly not possible for light-duty vehicles, but could be feasible for large combustion engines of trucks or busses.

An HEV is mainly powered by its combustion engine associated to a classical transmission system. The electric motor is used to assist the conventional engine when the efficiency of this latter is weak, i.e. at low charge or during vehicle acceleration. The electric motor uses the energy of the battery, which cannot be charged from the grid, but is charged during regenerative braking or while the vehicle is decelerating. For HEVs, the vehicle can be powered 100% by the electric motor, although typically only at low speeds and for short distances (less than 10 km). The main advantage of parallel-hybrid vehicles is the reduction of fuel consumption (and CO_2 emissions) in comparison with ICEVs, while being technologically close since they use a conventional combustion engine and transmission. The main drawbacks are the complexity of the hybrid system and the cost of the vehicle (batteries of HEVs are more expensive than those for BEVs due to the need of higher power-to-energy performance).

PHEVs are powered by an electric motor and an internal combustion engine able to work together or separately. The main specificities of a PHEV are the possibilities to charge the on-board battery from the grid and to travel a significant distance in full electric mode (typically 30 km to 60 km for current models). Consequently, PHEVs enter in the full-hybrid vehicles category. They can be either parallel, series or complex designs.

FCEVs are entirely powered by electrical energy that is produced by a fuel cell stack based on hydrogen contained in an on-board tank combined with oxygen from the ambient air. The main advantages of FCEVs are their long driving range and faster and green refuelling. However, fuel cell stack technology is complex and is still in an early stage of development. Few models of FCEVs are currently available on the market in comparison with other type of electric vehicles. The driving range of FCEV is typically between 150 km and 500 km.

A main advantage of BEV (and PHEV when driving in pure electric mode) is that there is no exhaust emission while driving, improving locally air-quality. However, emissions of non-exhaust Particulate Matters (PM_{10} and $PM_{2.5}$) for BEVs are comparable to those of ICEVs, due to the fact that BEVs are usually heavier than their conventional counterparts [7]. One should also keep in mind that the greatest effects for the reduction of CO_2

emission (and associated global warming reduction) occurs when BEVs are charged with electricity from nuclear and renewable sources, while the carbon footprint is very close to ICEVs when electricity is produced by coal or oil (cradle-to-grave calculations in [4]). Another advantage of BEV is the low engine noise, reducing the impact of road traffic noise on the populations, especially at low speeds in urban area for which engine noise of ICEV is usually dominating tyre/road noise. Noise emission of EV will be investigated in details in section 4. Finally, a main drawback of BEVs still remains their limited driving range compared to ICEVs and the long time needed to recharge the batteries. Therefore, future improvements should focus on better battery range, availability of recharging stations on the network, but also on the reduction of rolling resistance at the tyre/road interface [8] which represents about 40% of the total electric energy supplied to the vehicle during rolling according to [4]. In the following, the study will mainly focus on BEVs and PHEVs belonging to vehicle category M1, which will be designated by Electric Vehicles (EVs).

2.2 Current state of the European electric vehicle fleet

2.2.1 Electric passenger cars (M1 category)

According to IEA global EV outlook 2019 [9], EV deployment around the world has been growing rapidly over the last decade (Figure 2-1). The global fleet of electric passenger cars has been passing 5.1 million in 2018, which represents an increase of 63% from the previous year. In 2018, the worldwide distribution of EV fleet was as follows: around 45% of EV were in China, 22% of EV were in the United States and Europe accounted for 24% of the global fleet, which represents a total of 1.2 million of EV (of which 0.96 million were in European Union countries).

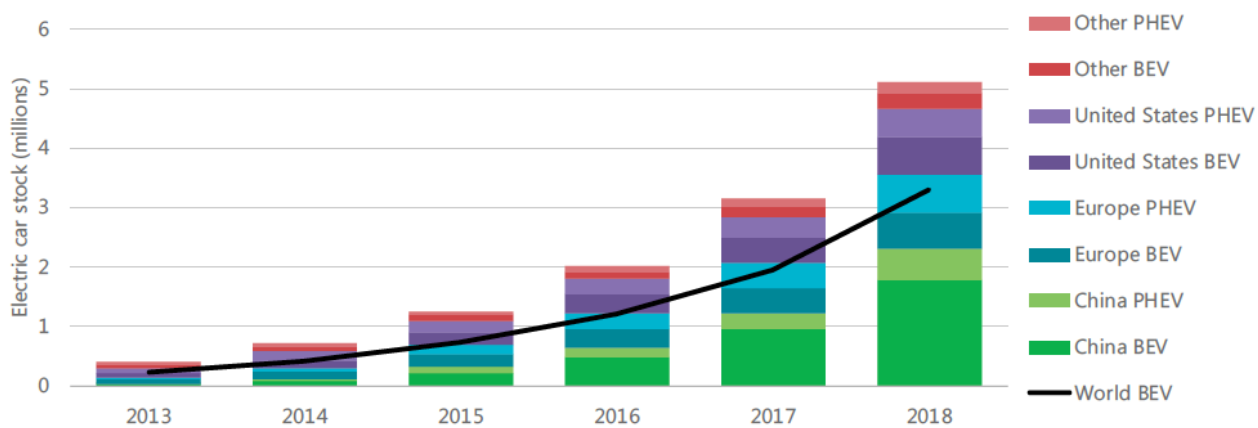


Figure 2-1 Passenger electric vehicle car stock over the world from 2013 to 2018 according to IEA global EV outlook 2019 [9]. A year-to-year growth rate of about 60% is observed since 2016.

These figures from IEA are in accordance with EAFO data for 2018 [2], which identify 1.27 million of EV in Europe of which 0.97 million were in European Union. Figure 2-2 gives the total number of electric passenger cars in the European Union between 2008 and 2019. At the end of year 2019, the total number of Alternative Fuels (AF) passenger cars in the European Union published on EAFO website was 1.27 million, of which about 0.65 million of BEV and 0.62 million of PHEV. Adding EFTA countries and Turkey increases the number of EV to 1.64 million over the European area (0.89 million of BEV and 0.75 million of PHEV), mainly due to the Norwegian market.

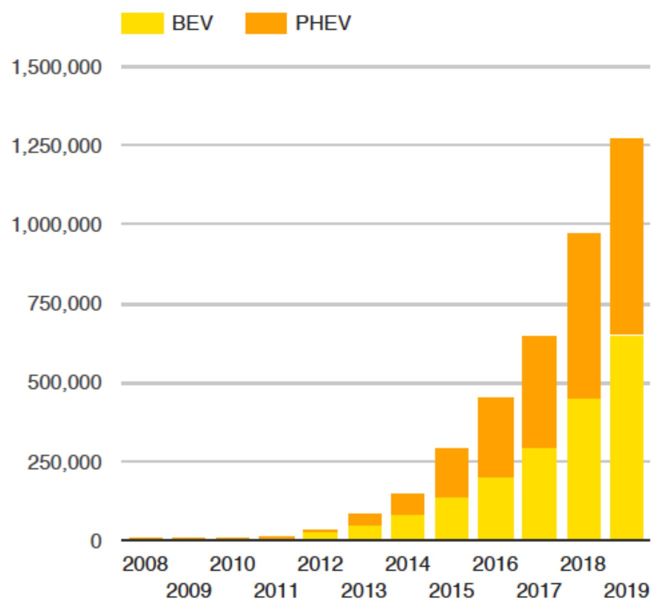


Figure 2-2 Growth of electric passenger cars in the European Union between 2008 and 2019 (Source: EAFO [2]).

According to [2], Table 2-1 gives the top five countries AF fleet of passenger cars within European Union. About 1 million of EV (i.e. 79% of the total fleet) are located in these countries, namely Germany, United Kingdom, France, Netherlands and Sweden. Regarding new registrations of EV in 2019, the same ranking is observed within the countries, but when looking at the market share of new registrations of EV over the total vehicle fleet, the top five countries are Sweden (11%), Netherlands (10%), Finland (6%), Portugal (5%) and Ireland (4%). The market share of new registrations of EV over the European area (including EFTA countries and Turkey) has been reaching 3% in 2019, increasing by one point per year since 2017. By far Norway is the most dynamic market for EV, with a total fleet of 310,170 vehicles and a market share of new registrations of EV reaching 55% in 2019.

Table 2-1 Top five countries alternative fuel fleet of passenger cars within European Union [2].

Country	**Total number of AF cars**	**Total number of new registrations**
Germany	265,979	83,989
United Kingdom	247,492	55,792
France	208,176	48,722
Netherlands	173,438	36,393
Sweden	105,588	31,137

The number of available electric passenger cars models in Europe up to 2017 has been listed from EAFO data in JRC report [10]. The evolution of EV models from 2010 to 2017 is shown in Figure 2-3. Concerning BEV, the number of models was already consistent in 2010, has been steadily increasing until 2014 and then stabilised around 30 models up to 2017, reaching twice the number of 2010. Regarding PHEV, while almost inexistent in 2010, the market growth has been quite impressive and the number of models has overtaken BEV since 2016. According to AVERE-FRANCE [11], 29 BEV models and 31 PHEV models were available for sales on the European market at the beginning of 2020. By comparison, 16 BEV models and 4 PHEV models have been listed in the literature review of the LEO project [12], probably based on 2012 data.

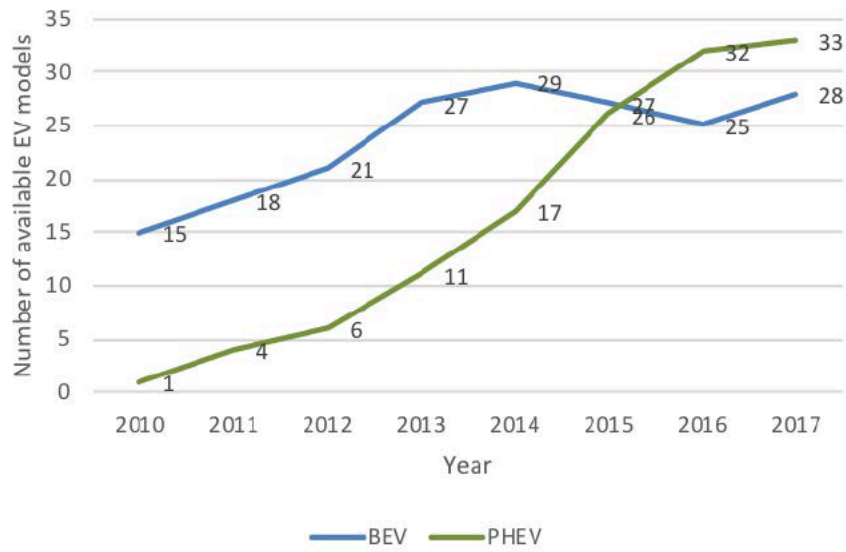


Figure 2-3 Number of available models of electric passenger cars from 2010 to 2017 (Source: JRC [10]).

Figure 2-4 gives the distribution of current BEV and PHEV models available by car segments. Excluding SUV (J segment), the distribution over segments is different between BEV, which dominates in the smaller car segments (A to D), and PHEV, which dominates in medium and large car segments (C to F). It is noticed that PHEV are not available for small cars segments (A and B) and that BEV are unavailable in luxury cars and sport coupés segments (F and S). The SUV segment J makes exception with almost equal number of BEV and PHEV models available, but one should remind that the SUV segment includes a wide range of vehicle sizes.

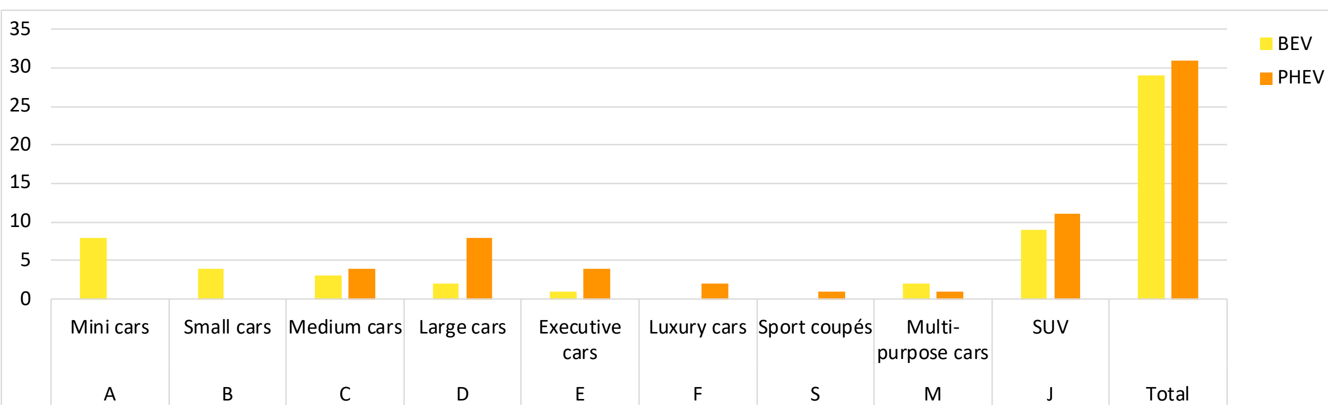


Figure 2-4 Numbers of BEV and PHEV models available for sales on the European market and distribution by European standard car segments (own elaboration from AVERE-FRANCE website data [11] on January 2020).

The transition to electric mobility has definitively been initiated by Original Equipment Manufacturers (OEMs). Each OEM has its own electrification strategy for the next years and a number of announcements have been made in 2018 and are listed in details in [9]. Figure 2-5 gives the distribution of BEV and PHEH models presently available on the electric automotive market by main OEM. In terms of number of models, German OEMs (BMW, Daimler-Benz and Volkswagen group) dominate in the PHEV domain, while French and Asian OEMs (PSA, Renault-Nissan-Mitsubishi and Hyundai-Kia) dominate in the BEV domain. Tesla Motors (USA) only proposes BEV models contrary to AB Volvo (Sweden) of which 100% of models are PHEV.

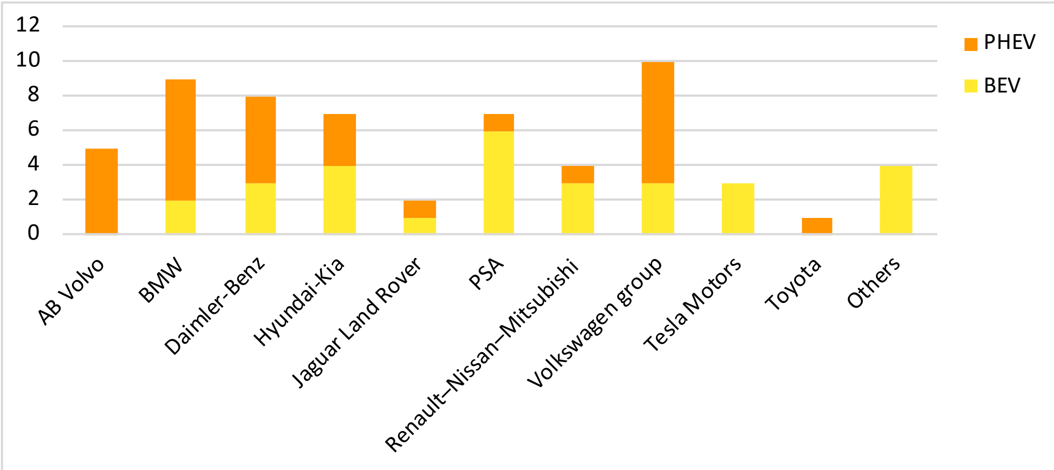


Figure 2-5 Distribution by OEM of BEV and PHEV models available for sales on the European market (own elaboration from AVERE-FRANCE website data [11] on January 2020).

Figure 2-6 gives the top 10 models as a percentage of the total fleet of BEV (left) and of the total fleet of PHEV (right). The figures are according to EAFO data [2] updated on October 2019. The BEV fleet is by far dominated by the Renault Zoe (18%) and the Nissan Leaf (16%), followed by the BMW i3, the Tesla Model S, the VW e-Golf and the Tesla model 3, each model representing about 8% to 9% of the total BEV fleet. Concerning PHEV, the market is by far dominated by the Mitsubishi Outlander (18%), while each of the other models do not exceed 6% of the total PHEV fleet.

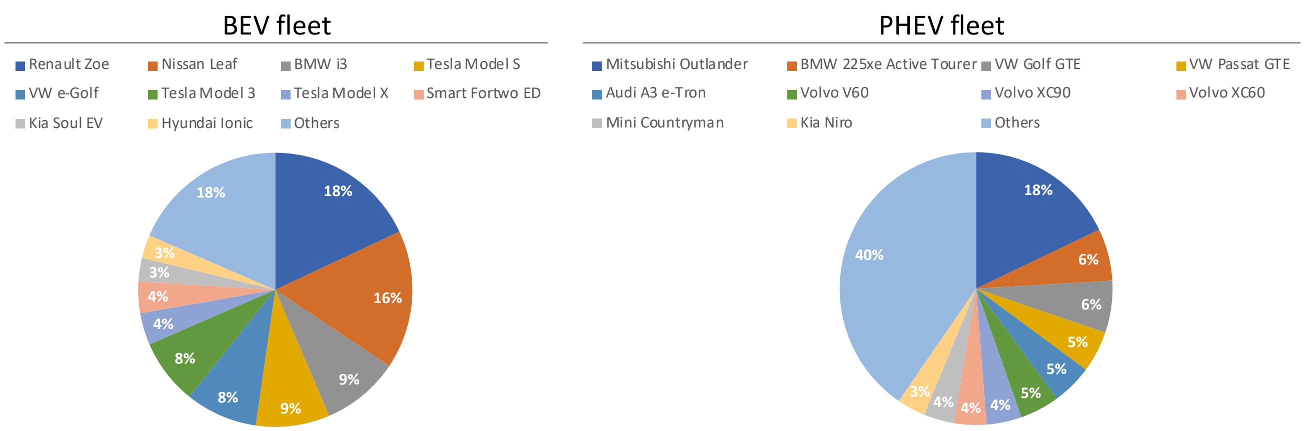


Figure 2-6 Top 10 models of BEV (left) and PHEV (right) as a percentage of the total fleet for each category in the European area (own elaboration from EAFO [2] – October 2019). The total number of BEV is 946,125 and the total number of PHEV is 587,647.

According to [2], Figure 2-7 and Figure 2-8 give the top ten of new registered models in the European area between January and November 2019, for BEV and PHEV respectively. Concerning BEV, the Tesla Model 3 is by far dominating the new registrations in 2019, followed by the Renault Zoe, the Nissan Leaf, the BMW i3 and the Volkswagen e-Golf. Regarding PHEV, the best seller in 2019 is the Mitsubishi Outlander, confirming its domination on the market. However, thinking in terms of OEM, the PHEV market is better balanced with 4 BMW models, 2 models for AB Volvo and 2 models for Hyundai-Kia. Finally, Figure 2-9 gives a picture of the top 6 electric passenger cars models for new registrations in 2019 in the European area, namely Tesla model 3, Renault Zoe, Nissan Leaf, BMW i3 and Volkswagen e-Golf for BEV and Mitsubishi Outlander for PHEV.

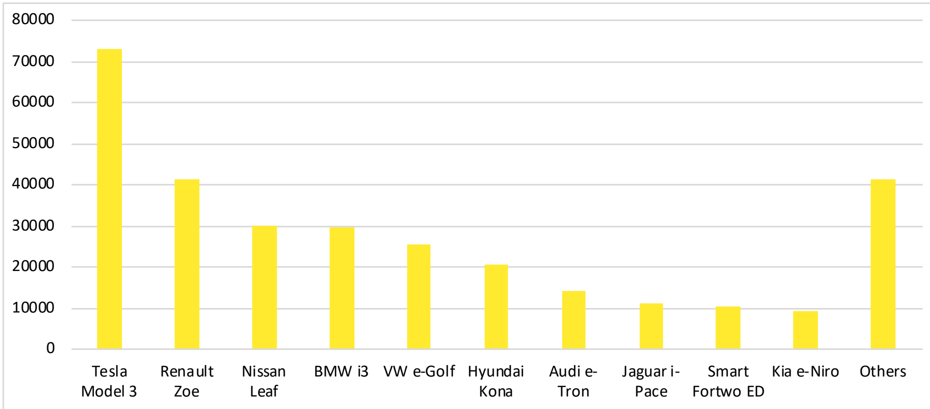


Figure 2-7 Top 10 of new registered BEV models between January and November 2019 in the European area, i.e. European Union and EFTA countries (own elaboration from EAFO [2]).

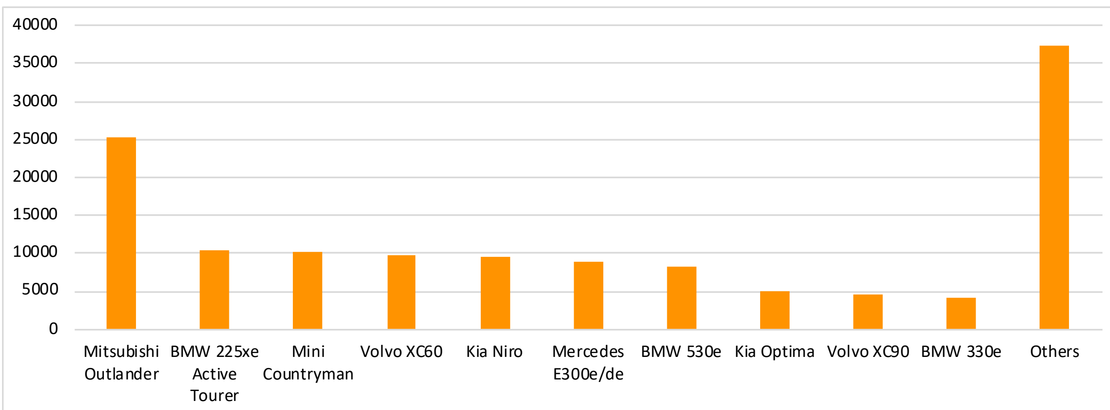


Figure 2-8 Top 10 of new registered PHEV models between January and November 2019 in the European area, i.e. European Union and EFTA countries (own elaboration from EAFO [2]).

Tesla Model 3 (BEV)
Segment D

Renault Zoe (BEV)
Segment B

Nissan Leaf (BEV)
Segment C

BMW i3 (BEV)
Segment B

VW e-Golf (BEV)
Segment C

Mitsubishi Outlander (PHEV)
Segment J

Figure 2-9 Top 6 EV models for new registration between January and November 2019 in the European area.

2.2.2 Other vehicle categories

Light Commercial Vehicles (N1 category): According to [9], there were almost 250,000 Electric Light Commercial Vehicles (ELCVs) on the worldwide road network in 2018. The largest market for ELCVs was China followed by Europe with respectively 57% and 38% of the global stock. The market of ELCVs is dominated by BEVs (99%). This brings the number of electric light-duty vehicles on the road worldwide to about 5.4 million in 2018. Figure 2-10 gives the total number of ELCVs in the European Union between 2008 and 2019. As for BEV passenger cars in Figure 2-2, the fleet of ELCVs is constantly growing since 2015. At the end of year 2019, the total number ELCVs in the European Union was about 104,000, by 99,7% composed of BEVs. The most important part of the ELCVs fleet is by far located in France (47%), followed by Germany (20%). The same country ranking was observed for new registrations in 2019. According to [10], the Nissan e-NV200, the StreetScooter WORK, the Renault Kangoo ZE, the Peugeot Partner EV and the Citroën Berlingo EV were the top five ELCV models for registration in 2017.

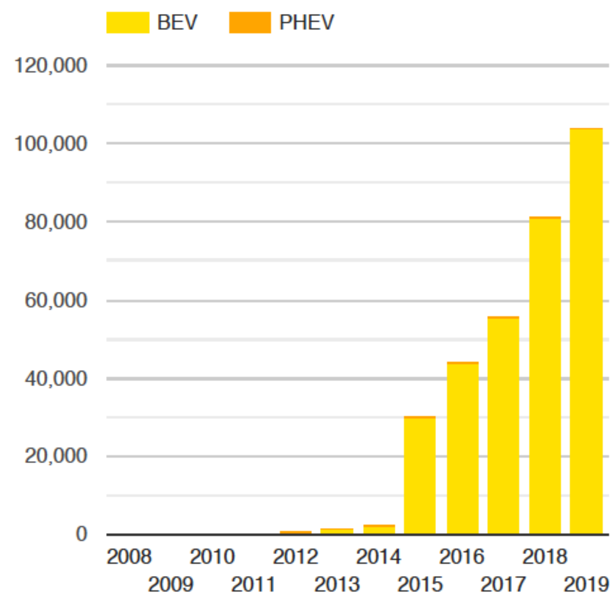


Figure 2-10 Growth of electric LCV in the European Union between 2008 and 2019 (Source: EAFO [2]).

FCEVs: As mentioned before, FCEVs remain marginal with a fleet of only 11,200 passenger cars worldwide, more than a half being located in the United States [9]. According to Figure 2-11, even if the fleet has been growing in the European Union since 2013, the total number of FCEVS in 2019 was only about one thousand [2]. Only three FCEV models were sold in 2019 in EU, i.e. Hyundai Nexo, Toyota Mirai and Hyundai ix35.

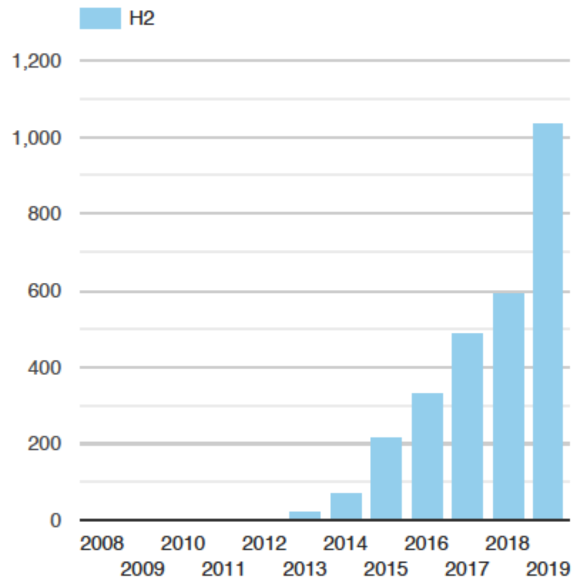


Figure 2-11 Evolution of FCEVs fleet in the European Union between 2008 and 2019 (Source: EAFO [2]).

Small electric vehicles for urban transport: This category of vehicles groups electric two or three-wheelers, low-speed electric vehicles, electric foot scooters and electric bikes. According to [9], while marginal in the European area, the electric two-wheelers market is dominated by China, which produced 26 million in 2018 and had an estimated 250 million units in circulation, over one-quarter of the global motorised two-wheelers stock (800 millions). The stock of electric three-wheelers exceeds 50 million in China and is about 2.4 million in India. Low-Speed Electric Vehicles are mainly located in China were owners are exempted from registration fees. The fleet was estimated to exceed 5 million vehicles in 2018 [9]. According to [13], the market of electric bikes has been growing significantly between 2006 and 2016, reaching a total number of about 1.7 million of e-bikes sold in the EU in 2016. The number of electric foot scooters all around the world has also been growing exponentially since 2017 [9], mainly in the United states and in the European area.

Buses (M2 and M3 categories): According to [9], the global stock of electric buses has been reaching about 460,000 vehicles in 2018, with China dominating 99% of the market. However, Figure 2-12 shows that the market of BEV and PHEV busses has been growing in the European Union since 2010. In 2019, the total number of electric busses in EU was about 3,600. The market is dominated by the Netherlands (22%), the United Kingdom (15%), Sweden (11%), Germany (7%) and France (7%).

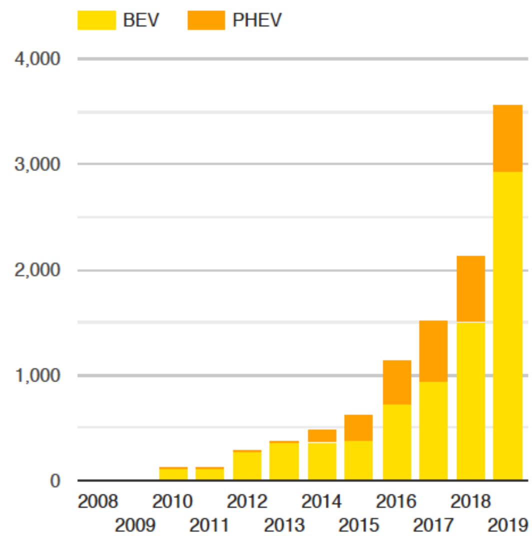


Figure 2-12 Growth of electric busses in the European Union between 2008 and 2019 (Source: EAFO [2]).

2.3 Outlook for the electric vehicle fleet

According to relevant publications, JRC report [10] provides an overview of the projections for EV market share in the next decades in Europe. From one study to another, figures can differ, but the trend is an increase of EV market share reaching about 40% in 2030, 60% in 2040 and 80% in 2050. According to IEA [9], the targets for the development of electric mobility are defined at different levels: country-level targets settled by governments and city-level targets based on announcements at a more local level. For instance, within European Union, a number of governments have announced bans on the sales of ICEV or sales targets for 100% Zero-Emission Vehicle (ZEV) within the next decades, i.e. in 2030 for Denmark, Ireland, the Netherlands or Slovenia and in 2040 for France, Portugal, Spain or United Kingdom. Norway aims at 100% ZEV sales by 2025 for light-duty vehicles and busses.

To support these targets, many policies have been adopted by the European Union. In 2019, the European Parliament adopted new CO_2 emission standards for light-duty vehicles, consisting in a reduction of CO_2 emission per km by 37.5% in 2030 for a new car, compared with 95 g CO_2/km required for 2021 [14]. For a new van, a reduction by 31% is foreseen, compared with 147 g CO_2/km required for 2021. These thresholds will encourage the sales of more BEVs and PHEVs. Manufacturers exceeding production shares of 15% of EV in 2025 and of 35% in 2030 will be rewarded by means of a less strict overall CO_2 target (up to 5%). EU also encourages the use of incentive schemes for electric mobility in European countries. EU promotes the development of battery industry in Europe via the European Battery Alliance and the increase of charging infrastructure capacity via new policies.

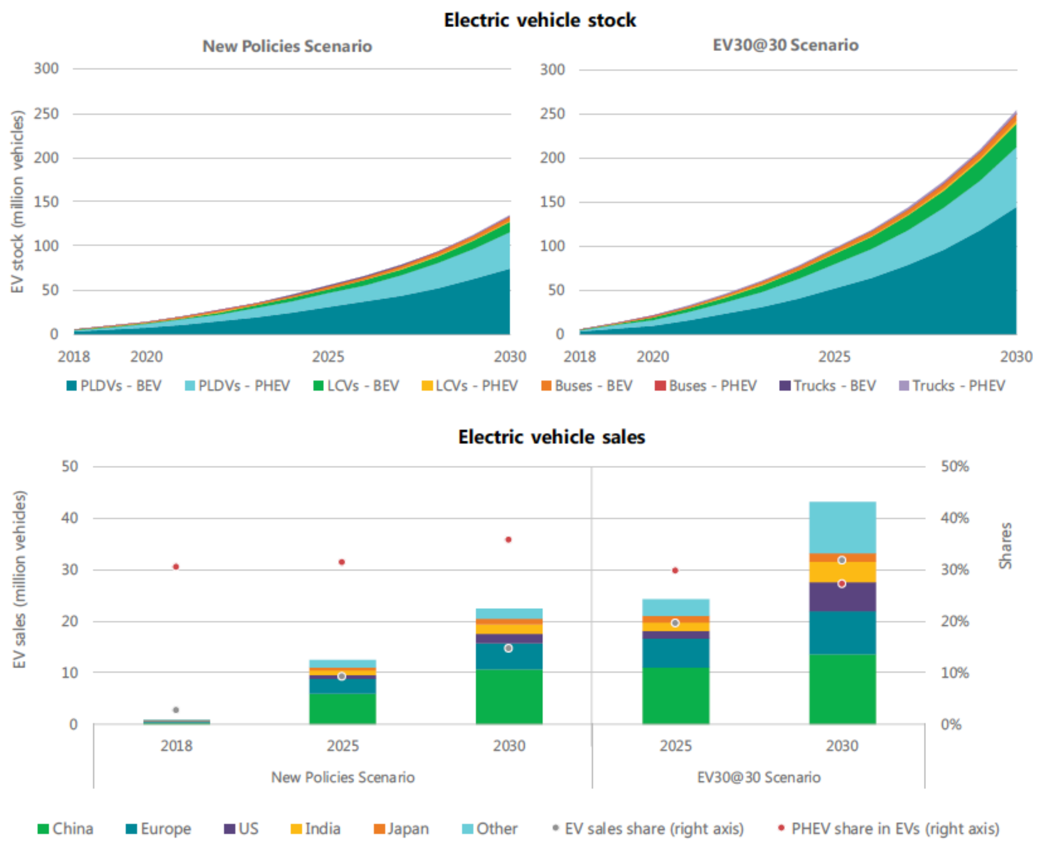
Consequently, the number of OEM announcements related to their electrification strategy has been increasing in 2018/2019. According to [9], examples of such OEM announcements related to EVs are listed below:

- **BMW**: “15% to 25% of group’s sales in 2025 and 25 new EV models by 2025”;
- **Ford**: “40 new EV models by 2022”;
- **Mercedes-Benz**: “0.1 million sales in 2020, 10 new EV models by 2022 and 25% of group’s sales in 2025”;
- **PSA**: “0.9 million sales in 2022”;
- **Renault-Nissan-Mitsubishi**: “12 new EV models by 2022. Renault plans 20% of the group’s sales in 2022 to be fully electric”;
- **Tesla**: “about 0.5 million sales in 2019 and a new EV model in 2030”;

- **Toyota**: "more than ten new models by the early 2020s and 1 million BEV and FCEV sales around 2030";
- **Volkswagen**: "0.4 million electric car sales in 2020, up to 3 million electric car sales in 2025, 25% of the group's sales in 2025, 80 new EV models by 2025 and 22 million cumulative sales by 2030";
- **Volvo**: "50% of group's sales to be fully electric by 2025".

Thus, the number of EV models available on the market is expected to increase significantly in the next years. According to [9], BEVs and PHEVs models are likely to be more equally distributed over car size segments, but PHEVs will probably not be available for the small car segment.

Regarding projections to 2030, two different scenarios are considered in [9]: the New Policies Scenario, which predicts the consequences of the current announced policies, and the EV30@30 scenario, which is based on the ambitions of the Electric Vehicle Initiative of IAE member countries and aims to achieve 30% market share for EVs in all modes by 2030. Figure 2-13 shows that in 2030, global sales of EV reach 23 million and the stock exceeds 130 million vehicles in the New Policies Scenario. In the EV30@30 scenario, EV sales and stock are likely to double by 2030, with 43 million EV sold and a worldwide EV fleet exceeding 250 million. BEVs will represent the most important part of the fleet, followed by PHEVs. China will stay the first market for EVs, followed by Europe. Market share of EV should reach about 15% in the New Policies Scenario, while by definition it will be 30% in the EV30@30 scenario.



Note: PLDVs = passenger light-duty vehicles; LCVs = light-commercial vehicles; BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle.
Source: IEA analysis developed with the IEA Mobility Model (IEA, 2019a).

Figure 2-13 Global EV stock and sales outlooks from 2018 to 2030 (Source: IEA [9]).

2.4 Conclusions in connection with LIFE E-VIA project actions

Since the last decade, electric vehicle market has been growing fast worldwide, especially in the European area where about 1.4 million of light vehicles are in circulation at the end of 2019. With 1.3 million of electric passenger cars, the European market is dominated by BEVs and PHEVs of the M1 category, completed by about 0.1 million of electric light commercial vehicles (N1 category). The market share of new registrations of EVs over the European area has been reaching 3% in 2019. Depending on projection scenarios, it is planned to reach between 15% and 30% of the global vehicle fleet by 2030. BEV and PHEV in the light vehicle category should stay the dominant market in Europe. Consequently, the LIFE E-VIA project will focus on this category of vehicles within actions B1 to B7.

Recently, many governments of European countries have fixed targets for the development of electric mobility, with the aim of reaching 100% ZEV between 2030 and 2040. These announcements are supported by new policies adopted by the European Parliament increasing the requirement on CO_2 emission standards for new light vehicles models in 2021. Consequently, OEMs are adopting an electrification strategy for the next years and the number of BEVs and PHEVs available on the market is likely to increase significantly. At the end of 2019, there were approximately 60 models of EVs available for sale in the European area, with almost equal number of BEVs and PHEVs. The distribution over segments is different between BEVs, which dominate in the smaller car segments (A to D), and PHEV, which dominate in medium and large car segments (C to F). Segment J for SUV is balanced between BEVs and PHEVs. However, new registrations by volume in 2019 are clearly dominated by BEV models. The Tesla Model 3 is by far dominating new registrations in 2019, followed by the Renault Zoe, the Nissan Leaf, the BMW i3 and the Volkswagen e-Golf. These models are also dominating the total fleet in the European area. Therefore, within action B2 of the LIFE E-VIA project, it was decided to consider these BEVs for acoustics tests on the reference test track in Nantes (France). To be representative of the current European fleet of EVs, at least one model per available segment will be considered in vehicle category M1:

- Segment B: Renault Zoe and/or BMW i3;
- Segment C: Nissan Leaf and/or VW e-Golf;
- Segment D: Tesla Model 3.

An additional model will be considered in vehicle category N1:

- Renault Kangoo ZE.

Noise characterisation of these BEVs within B2 will also be used for improvement of CNOSSOS EU model planned in action B6, based on the noise characteristics of vehicles representative of the current EV fleet in Europe.

***Addendum**: The unprecedented global health situation occurring in 2020 due to COVID19 outbreak and its economic repercussion might introduce changes in the future trends for the development of electric vehicles in Europe.*

3 Changes of driving behaviour impacting noise emission

Electrically driven vehicles encounter differences from conventional engine vehicles, either regarding technological (motor characteristics, regenerative braking) or surrounding/sensorial (noise emission, acceleration or torque) aspects, that may involve a driving change from the driver. Beyond the specificities of vehicle noise sources (section 4), this may directly affect the kinematic preferences (speed, acceleration or deceleration rate) used along a driving route and, consequently, impact the noise generation and balance the contribution of sources differently.

A first section (§ 3.1) considers the main EV technological characteristics likely to modify the driving behaviour and a second section (§ 3.2) deals with the results available from scientific studies on EV driving styles that are relevant for noise emission. Section 3.3 synthesizes the main implications for actions of the LIFE E-VIA project.

3.1 State of knowledge on driving behaviour specific to electric vehicles

3.1.1 Technological aspects

Three main technological specificities of EVs are of particular importance in the context of the project: the specification parameters of the electric motors, the battery energy storage and the regenerative braking.

3.1.1.1 Electric motor

The motor characteristics are the basis of the vehicle dynamics, specifying the power and torque supply in operating conditions. The optimal working areas differ greatly between a conventional engine and an electric motor, as their efficiency behaves differently over torque and speed ranges (Figure 3-1 and Figure 3-2). The optimum area of the conventional engine covers a limited rotational speed, making the use of a gearbox necessary for providing the required torque on a wide vehicle speed range. However, the electric motor offers good efficiency and torque over a wide rotational speed range, making the use of a gearbox unnecessary. The maximum torque is available as soon as the vehicle starts until the maximum power is reached, the latter remaining available up to the maximum speed [15]. The constant torque offers acceleration ability over the whole motor speed range [16].

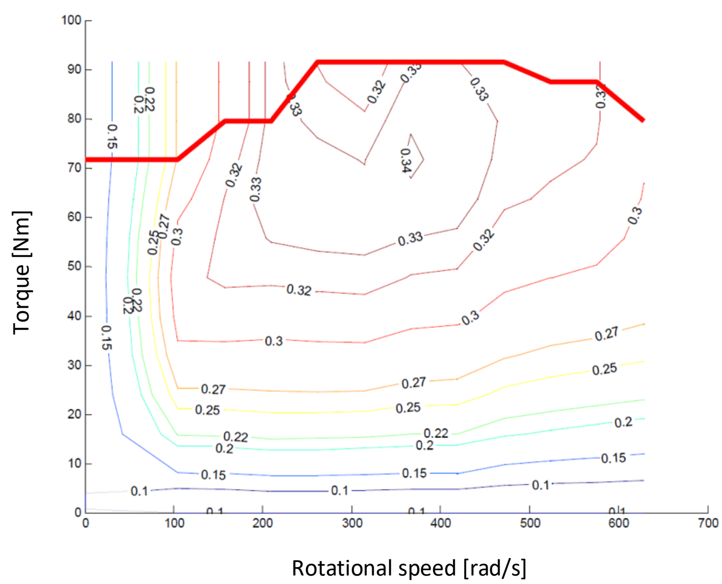


Figure 3-1 Example of efficiency map of a gasoline engine (the red line is the maximum torque curve) [17].

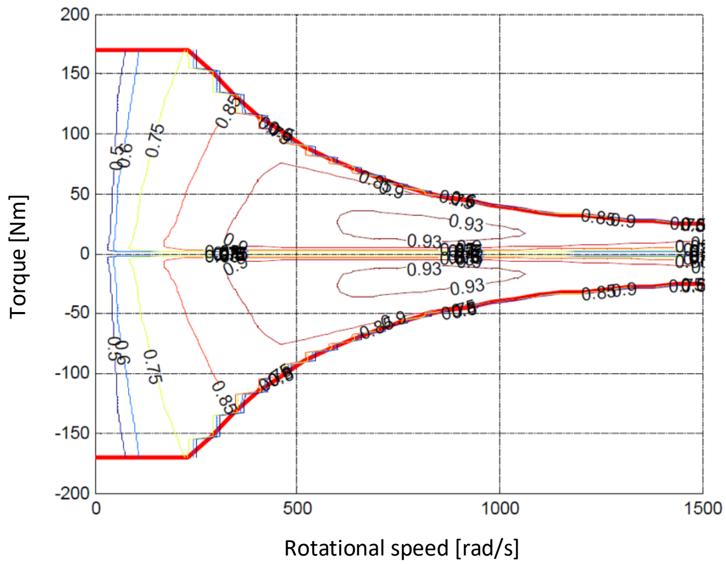


Figure 3-2 Example of efficiency map of an electric motor (permanent magnet motor) [17].

Electric motors offer a far better energy efficiency than conventional engines, meaning a higher kinetic energy available for the same amount of potential of energy (respectively from electricity and from chemical potential of fuel). However, energy storage is a weakness of battery electric vehicles, key issue defining the available vehicle range.

3.1.1.2 Energy consumption, storage and vehicle range

The vehicle range is a well-known drawback of full electric vehicles, although improvements are constantly being introduced to the EV market. Beyond the power requirement, a main factor of the vehicle range is the battery energy density, either gravimetric (Wh/kg) or volumetric (Wh/L), limiting the maximum energy stored in the vehicle and consequently its driving range. Thus, improvements are needed for battery weight reduction and Li-ion batteries offer particularly attractive performance in this regard, with overall cost reduction as well [18].

Obviously, power demand, acceleration and vehicle speed play a significant role in the vehicle energy consumption, the speed being the main factor, then the quantity of acceleration events and at a lower level the acceleration rate [19]. In this, the driving style affects the energy consumption and, consequently, the vehicle range. Beyond the vehicle technology and the driver’s attitude, the traffic condition also influences the driving style. A study relying on a conventional traffic pointed out the dominant use of a milder driving style in a heavy traffic, whereas an aggressive driving style is more common in a light traffic [20]. Applied to electric vehicles, this driving style imposed by the traffic affects energy consumption and also battery ageing.

3.1.1.3 Regenerative braking

Full electric and hybrid electric vehicles are equipped with regenerative braking. This allows the battery to recover energy and recharge during deceleration through the conversion of kinetic energy into electricity, thus reducing energy loss from friction braking. However, it was shown that an aggressive or inappropriate use of regenerative braking may seriously decrease the energy efficiency. Depending on the vehicle concept, the regenerative system may be activated either as soon as the “gas pedal” is released or by the actuation of the brake pedal. The latter concept is common in EVs and HEVs, generally providing a deceleration close to the one of conventional vehicles (concept 2 of Figure 3-3) [21]. The former concept offers the highest energy recovery when the acceleration pedal is fully released, with a higher drag torque (concept 3 of Figure 3-3). The vehicle may be brought almost to a standstill with action on the sole gas pedal. This has been tested on the Mini-E, in preparation of the BMW i3 development, with deceleration rates up to -2.3 m/s^2 [16].

In terms of efficiency, energy recovery is maximized if the driver-imposed deceleration is not to sharp, so that the motor regeneration torque is sufficient and no use of mechanical brakes is needed [22].

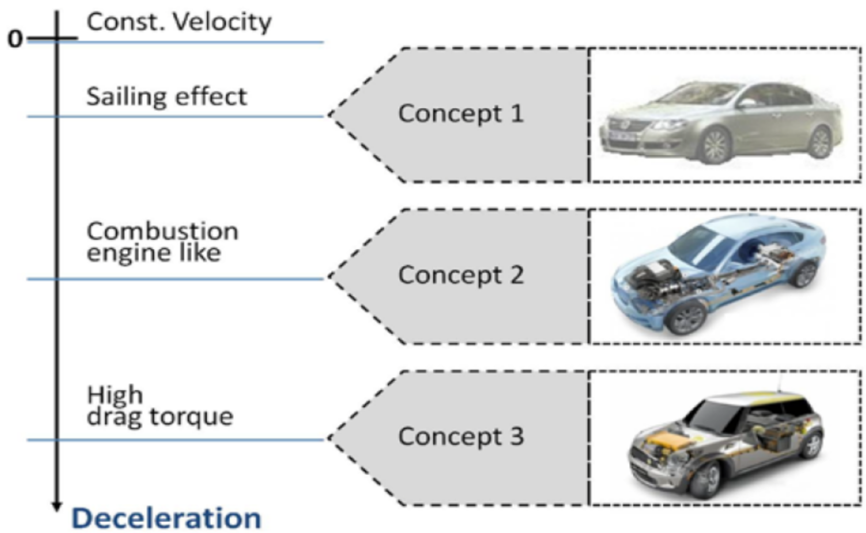


Figure 3-3 Different concepts of EV deceleration and regenerative braking [21].

3.1.2 Changes in driving style by EV drivers

A fairly large amount of studies have been considering the driving behaviour on EVs, whether for the derivation of specific driving cycles, the insight of acceptability of these new vehicle types, the adaptation to particular technological elements (regenerative braking) or for safety concerns [23]. Various views have been considered, either the driver's point of view or objective data from a data logger set on-board the vehicle, involving either new or experienced EV drivers, on various time scales. The literature review reported below is not exhaustive, preferably focusing on publications no older than 2010 due to the rapid evolution of EV technologies and performance. Studies often investigate many different aspects that are beyond the scope of the LIFE E-VIA project. Only lessons relevant to the project are synthesised below.

Incidentally, it is worth noticing a study conducted in Florence (Italy) [22]. Considering the spread of electric vehicles in and around the city of Florence, in relation to the restricted access to the city centre except for electric vehicles as well as to other incentives favouring electromobility, it has been the site of investigations for developing driving cycles representative of electric vehicles. For this purpose, various light EVs have been equipped with sensors and monitored during a rather long period (9 months), allowing the examination of driving styles among other things. The vehicle types included several Renault Kangoo ZE, as light commercial vehicles (class N1), and Peugeot Ion or Citroën C-Zero – which are actually identical vehicles – as passenger cars (class M1). This study provides an interesting connection with LIFE E-VIA, regarding both the location and vehicles since Florence is the test case city of LIFE E-VIA and Renault Kangoo ZE model will be a test vehicle in action B2. This will be cited at various points in this section.

Several factors may incite a different driving style with EVs compared to conventional ICEVs [24]:

- the limited vehicle range;
- the availability of regenerative braking;
- different sensations (acceleration, torque, acoustical perception).

3.1.2.1 Limited vehicle range

Managing the energy stored in the vehicle, motivated by "range anxiety" or by energy saving concerns, has a significant influence on EV drivers. It turns out that these often use a smoother driving style as a mean to extend the vehicle range [25]. This is emphasized if the available energy might be tight for the intended route, if the remaining range falls [26] or if charging points are unavailable [22]. "After a few months of use, eco-driving is taking place" [25] and this adaptation tends to become a habit.

A long-term case study performed in Portugal investigated the impact of EV driving on the driving behaviour [27], both on private and fleet users, with slightly different attitudes between both groups. After five months, about most EV drivers considered that they had changed their driving style, with a lower speed (78% for private users *vs* 17% for fleet users), a less aggressive and more efficient driving for a quarter of them, but a more aggressive driving for 38% fleet users [28].

Another study conducted in Germany emphasized, after the same duration, "a significant difference in the driving habits of an internal combustion vehicle and that of an electric vehicle". Although the average speeds did not differ, acceleration was smoother and EV users drove at more consistent speeds [16]. This has also been recently confirmed by an American survey study involving drivers of plug-in electric and hybrid-electric vehicles [29].

Generally speaking, EV drivers show anticipation, use deceleration to efficiently benefit from the regenerative braking (as detailed below) and try to drive economically by favouring smooth deceleration and acceleration and keeping a constant speed as far as possible [16][30][31][32][33]. They may even avoid to decelerate if conditions permit [34]. On country roads or highways, they may reduce average speed [16].

Also, EV drivers improve their expertise in constant speed driving when becoming experienced, with a higher percentage of constant driving than with conventional vehicles [16].

3.1.2.2 Availability of regenerative braking

Regenerative braking is a key factor in the change of driving style compared to conventional vehicles. Obviously, it has connections with energy optimisation and management for improving the vehicle range. Indications available on the dashboard are a strong motivation and guideline for the drivers to maximise energy recovery. The use of these indications could explain the lower mean deceleration observed on EVs in Florence study in comparison with those used in driving cycles representing conventional vehicles, although the authors cannot definitely assert whether this results from the tested vehicles, from the context of the city or from the tour mission, since lacking of a direct comparison with ICEVs in similar conditions [22]. However, these observations are consistent with other studies.

In particular, a wide study has been incited by BMW in several countries of the world, including Germany, UK, France and USA, aiming at understanding the driver's responses to Mini-Es. One main point concerned the strong regenerative braking, which was incorporated into the "gas pedal" (see section 3.1.1). After some learning period, shorter than a day, drivers could efficiently manage acceleration and braking with this sole pedal, increasing their skills with the help of the dashboard instrumentation and even feeling it as a game [30][35][36]. They reported to have a frequent use of regenerative braking and the learning period was rather short since several dozen of kilometres seemed sufficient to evidence the decrease of braking manoeuvres and the efficient control of deceleration (Figure 3-4) [37][35]. On motorway sections, after a training period the use of friction brakes was clearly lower on EVs than on ICEVs. This remained noticeable on arterial roads [16]. Although drivers experienced sharp acceleration and deceleration in the first test period, it turned out that despite the sporty feel due to the strong drag torque, much appreciated by drivers, the use of regenerative braking contributes then significantly to the smoother driving styles previously cited [16]. Therefore, smooth driving may reduce the number of starts and stops at low speed [22], with a direct benefit on energy consumption (see section 3.1.1).

An Austrian study (project E-FFEKT) investigated comparative tests conducted with 90 drivers driving an ICEV and an EV on a real-traffic route [38]. The differences on the vehicle longitudinal dynamics appeared negligible, although some high deceleration rates (-1 m/s^2) were noticed. However, this might arise from the short-term test duration (about 1 hour) corresponding to the learning EV driving phase and the behaviour could change on a longer term. The E-ENDORSE project concluded to the lack of deceleration difference between the vehicle types [39][40].

As a summary, after a rather short learning phase the regenerative braking leads to a higher control of deceleration, meaning softer and longer decelerations through anticipation and a reduction of the use of the friction brake, resulting in lower deceleration rates – or even no change at all – compared to ICEVs.

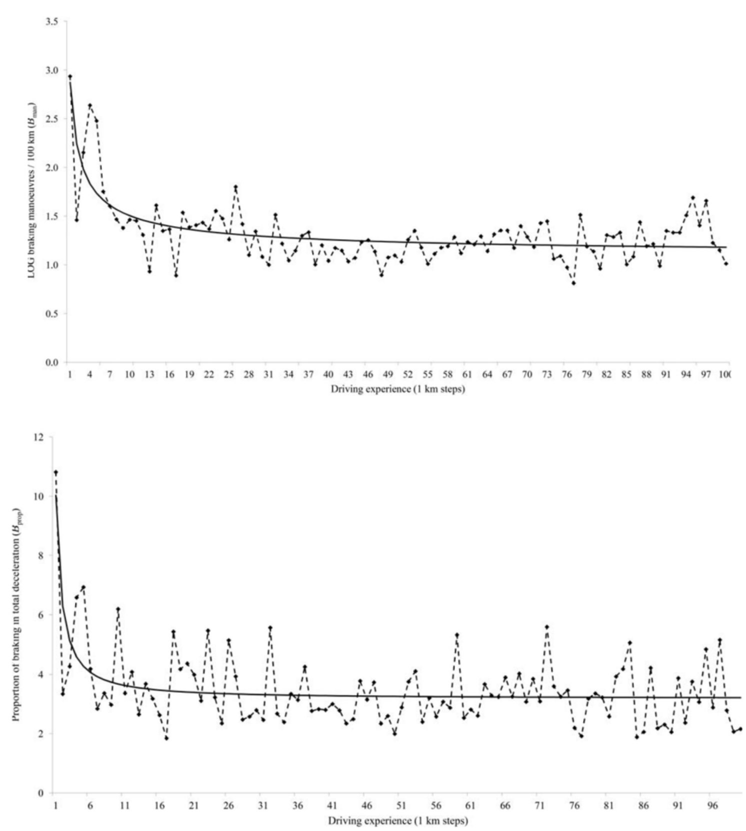


Figure 3-4 Number of actions on the braking pedal (top) and ratio of this number of actions to the deceleration duration (bottom), as a function of the distance covered up to 100 km in 1 km steps [37].

3.1.2.3 Effect of the different perception of vehicle performance and surroundings

E-drivers have a perception of the vehicle, either from technical performance (acceleration ability and torque availability) or from acoustical feedback, which differs from conventional vehicles and may affect their driving behaviour [22].

Changes due to the powerful technical capacities of EVs have often been outlined and give some contradictory outcomes. With a quite powerful EV, drivers report appreciating the fast acceleration [30] and driving faster because of the power availability [36]. Also with less powerful and older generation EVs, a higher minimum acceleration was noticed by Alessandrini et al. [15] compared to conventional driving cycles, with frequent moderately strong acceleration at low speed – even for non-aggressive drivers – presented as unintended and attributed to the lower interior noise and the different acoustical feedback.

However, in their study comparing drivers on EVs and ICEVs on a 45 km real-traffic round trip, Aleksa et al. [38] noticed “more events of strong acceleration for the ICEVs”. A focus on the longitudinal accelerations during 10 seconds after a complete stop pointed out “much smoother and lower peak accelerations with EVs”, with a higher gap for sporty than for moderate drivers. In fact, more differences resulted “from the system of power transmission (automatic or manual) than from the nature of the engine”, with a quite similar behaviour of ICEVs with automatic gearshift and EVs. A different approach involving a professional driver – to exclude adaptation effect – on a test track [39], performing accelerations up to given target speeds in accordance with a normal urban traffic with couples of similar EVs/ICEVs, led also to smaller acceleration values with EVs despite the high and constant torque capacities of the electric motors (see Figure 3-2).

If not for sporty reasons, the occurrence of increased acceleration rates is often explained by the reduced EV interior noise, blurring the driver references [15]. Investigating the influence of this low acoustic feedback on the driving speed, tests conducted with 20 drivers on several EVs and ICEVs completing an acceleration up to given urban target speeds, while the speedometer was hidden, showed no difference between both vehicle types on average [41]. The error on the speed reached by the driver was low on average, decreasing with the target speed, but with a quite large variance. Actually, drivers might mainly take advantage of visual information and of their experience. Concerning acceleration, the emergence of high frequency tones within EV interior noise seems to provide necessary sound feedback to the driver [41].

Finally, still on the low noise characteristics of EVs but from an outside point of view, we may wonder whether the driver adapts his (her) driving behaviour and speed in situations where his (her) presence might be uneasily detected by other road users. Very fond of the low noise emission, it turns out that the drivers compensate the higher risk by increased vigilance rather than by a driving change, all the more when getting much experienced EV drivers, by the way being unfavourable to additional artificial sound signal [42].

3.2 Impact on vehicle kinematics and noise emission

The speed, acceleration and deceleration rates have a great effect on the contribution of the noise sources – rolling noise and propulsion noise (see section 4) – both in power and frequency content. They also play a crucial role in the forces involved in the tyre-road contact area.

Findings from the literature review point out various EV driving behaviours compared with conventional vehicles, often relying on a smoother driving with effects on speed, acceleration/deceleration rates and lengths, but also sometimes reporting more aggressive driving schemes noticed with fleet users or users having powerful EVs. The ongoing traffic conditions and vehicle range certainly play a central role in the adoption of one or the other attitude. Intensive use of regenerative braking, while reducing those of friction brakes, is also a specificity of EV (and HEV) driving. Table 3-1 details the items beneath these behaviours and the impact one can expect on noise emission and on traffic flow, the latter affecting traffic noise.

Table 3-1 Impact of driving style changes on noise emission components.

Driving scheme	Kinematic condition	Effect on noise
Smoother driving	More consistent speeds, possibly lower on motorways	Lower overall noise levels
	Anticipated deceleration • Lower deceleration rates • Deceleration on a longer distance	Lower propulsion noise Lower rolling noise Changed local traffic flow and speed
	Increased recourse to regenerating braking Reduced recourse to friction braking	Higher motor noise No brake noise
	Lower acceleration rates	Lower propulsion noise Lower rolling noise
	Less stop/start events	Changed local traffic flow and speed
More aggressive driving	Higher acceleration rates	Higher propulsion noise Higher rolling noise
	Higher deceleration rates • Recourse to friction brakes	Higher motor/rolling noise Brake noise

3.3 Connection and implication for LIFE E-VIA actions

Considering the direct impact of driving conditions on the physics of tyre-road contact on the one hand, and on the activation, strength and balance of noise sources on the other hand, specificities of driving behaviour shall be considered in the characterisation of tyre-road and vehicle noise emission. This regards particularly the pass-by tests involved in subsequent action B2:

- B2.2 and B2.3 – Acoustical characterisation of EVs on existing tracks and on the prototypal test section;
- B4.2 – Acoustical characterisation of EVs.

Whereas usual characterisation of rolling noise with regard to road surface mainly concerns steady speed driving as representative of a large part of driving conditions, variable speed driving is actually a common situation in urban areas. Typical EV driving behaviour highlighted in the literature confirms the interest of completing LIFE E-VIA test schedule by considering acceleration and deceleration situations, thus providing noise emission skills in relation with the diversified performance of the tested vehicles (see segments identified in section 2.4). Deceleration tests should include regenerative braking situations without frictional brakes as far as possible. Acceleration tests are also planned in sub-action B2.4 with the selection of optimised EV tyres.

Knowledge acquired might provide insight for future consideration of EV acceleration/deceleration in the European noise prediction method CNOSSOS-EU, defining correction terms concerning road sections before and after traffic lights and roundabouts.

4 Noise source emission of electric vehicles

Noise source emission of EVs have been studied in several research projects during the last decades. One can mention the following relevant projects:

- The European project **QCITY** (Quiet CITY transport, 2005-2009) steered by Acoustic Control (Sweden) and involving 25 other partners, which was funded by the European Community under the 6th Framework Programme;
- The European project **CityHush** (Acoustically Green Road Vehicles and City Areas, 2010-2012) steered by Acoustic Control (Sweden) and involving 12 other partners, which was funded by the European Commission within the 7th Framework Programme;
- The European project **COMPETT** (Competitive Electric Town, 2012-2015) between TOI (Norway), the Austrian Energy Agency, University College Buskerud (Norway), Kongsberg Innovation (Norway) and the Danish Road Directorate, which was jointly funded by Electromobility+ within the ERA-NET-TRANSPORT, Transnova and The Research Council of Norway, FFG of Austria and Higher Education Ministry in Denmark;
- The bilateral project **LEO** (Low Emission Optimised tyres and road surfaces for electric and hybrid vehicles, 2013-2016) between TUG (Poland) and SINTEF (Norway), funded by the Polish National Centre for Research and Development (NCBiR) within the Polish-Norwegian Research Programme CORE;
- The European project **FOREVER** (Future Operational impacts of Electric Vehicles on European Roads, 2013-2014), between TRL (United Kingdom), AIT (Austria), IFSTTAR (France), Trinity College Dublin (Ireland) and University of Bath (United Kingdom), which was funded by the Conference of European Directors of Roads (CEDR).

4.1 State-of-the-art on EV noise sources and their contribution according to driving conditions.

Significant EV noise sources concern aerodynamic noise (wind and fans), mechanical noise (rolling noise, bearings and gears) and magnetic noise from the electric motor, as well as the alert sound signal increasingly available on new EVs. Fans may concern battery cooling and the HVAC[2] system. Their prominence depends on the presence of masking by the other sources. However, powertrain noise (mainly motor noise), rolling noise and AVAS[3] are the main specific contributions on EVs. They are considered in this section.

4.1.1 Propulsion noise

Electric vehicles are acknowledged to be quieter than conventional vehicles, at least at low speed, this behaviour being ascribed to the lower propulsion noise contribution. Nevertheless, although this component is more silent it has frequency characteristics that make it audible, even unpleasant or annoying in some conditions. It may stand out more significantly, if other sources like rolling noise are mitigated. Concern on motor in previous studies has primarily considered interior noise, but some studies have explored external noise from an environmental perspective. First, specificities of electric vehicle motors and motor noise are presented. Then, an overview of the results from the literature will be provided.

4.1.1.1 EV drivetrain and electric motor noise emission

This section aims to point out useful information on the characteristics of the noise radiated by an EV powertrain, mainly the electric motor, mentioning technological aspects when helping the overall understanding of the noise concern. It relies on comprehensive knowledge available in several reference publications [43]–[45], thesis [46] [47] or lectures [18].

[2] Heat, Ventilation and Air-Conditioning
[3] Acoustic Vehicle Alerting System

EV drivetrain and motor specificities

As is evident, the main difference between the powertrain of conventional cars and the one of electric cars is the motor, internal combustion engine for the former and electric motor for the latter. More widely, it implies a lot of surrounding differences. The conventional powertrain involves a large number of components, including many moving parts – of whom the engine and the gearbox – and the exhaust system. The internal combustion engine is known to be a main noise contributor, with broadband spectrum characteristics and tones in the low frequency range. Instead, an electric car simply comprises an electric motor (most often AC motor), a reducer and a power electronic converter (motor drive) (Figure 4-1). This converter controls the motor operation. It acts as an inverter when the battery powers the motor for driving (by adapting voltage and current waveforms to the speed/torque demand through switching) and as a rectifier to recharge the battery during regenerative braking (when releasing the throttle pedal or braking). Otherwise, the motor is a central part of the drivetrain, bringing new types of noise sources, and requires a specific focus.

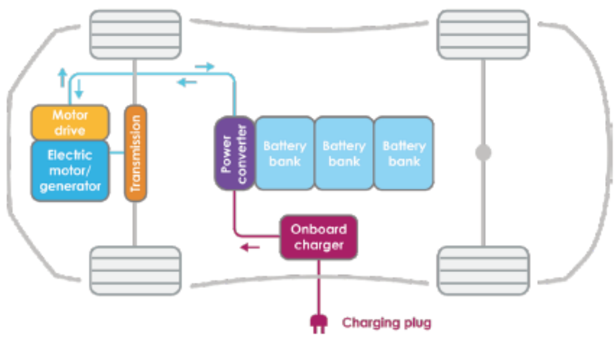


Figure 4-1 Principle of a full EV single-axis drivetrain (from [18]).

The electric motor offers a good energy efficiency on a wide operating speed range (Figure 4-2). It is characterised by a constant torque range (favourable to acceleration) from low speed up to a given base speed, at which begins a constant power range (favourable to high speed cruising). Urban driving should preferably operate near the base speed, with a high efficiency and a low noise. On light electric vehicles, electric traction does not generally require the use of a gearbox with multiple gear ratios and involves a fixed gear transmission through the reducer.

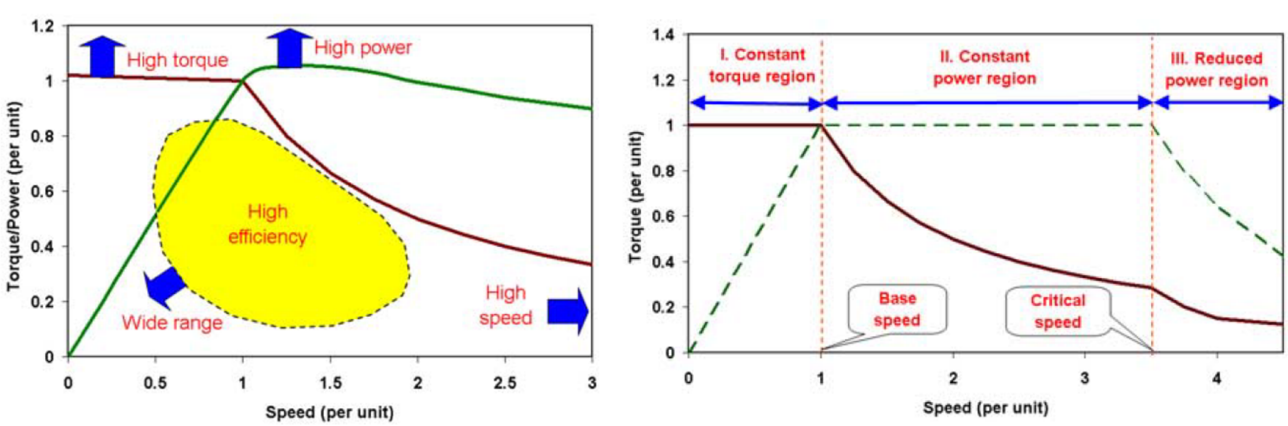


Figure 4-2 Torque/power requirements for traction machines (left) and idealised torque/power-speed characteristics (right) (from [43]).

Electric cars are generally equipped with AC motors. There are three main types of electric motors used in EVs, which may influence the noise emission differently, with respective strengths and weaknesses listed here non-exhaustively:

- The induction motor or asynchronous motor is simple to build, cheap and offers an easy speed control, but is not the most energetically efficient. It has much been used in EVs from the 2000s (Table 4-1).
- The permanent magnet motor or synchronous motor (PMSM) has the advantage to be light, efficient and silent but is more expensive and complex to control. It equips many electric vehicles nowadays. Another type of synchronous motor uses a wound rotor instead of permanent magnets.
- The synchronous reluctance motor is the most recent type, leveraging the advantages of both previous types. Thus, it is quite efficient, cheap but produces higher noise and requires advanced control. It has been rather used in prototype vehicles.

Table 4-1 Types of electric motors in several EV models.

<table>
<tr><th colspan="2">Motor type</th><th>Example of EV models</th></tr>
<tr><td colspan="2">Induction motor (asynchronous)</td><td>Tesla X90D
BMW Mini-E
Tesla Model S</td></tr>
<tr><td rowspan="2">Synchronous motor</td><td>Permanent magnet</td><td>Citroen C-Zero / Peugeot Ion
Chevrolet Volt / Opel Ampera
Fiat 500e (2013)
Smart Fortwo Electric
Tesla Model 3 / Model S
Nissan Leaf
Nissan e-NV200
Hyundai Ioniq
BMW i3</td></tr>
<tr><td>Wound rotor</td><td>Renault Zoe, Kangoo ZE</td></tr>
</table>

EV drivetrain noise sources

The different elements of an EV drivetrain can make a noise contribution. Practically, the electric noise sources from the power electronic controller seem difficult to separate from the motor noise. The reducer, which includes gears, may radiate a whining noise exhibiting speed-dependent tones. The electric motor is the main concern of EV propulsion noise.

Noise emission of the electric motor

A spectrum rich of strong tone components on a wide frequency range characterises the electric motor noise, including high frequencies unlike conventional engines. Three main mechanisms are involved in the noise generation (Figure 4-3), with specific spectral behaviours and contributions as illustrated in Figure 4-4 by the near-field noise pressure measured close to an electric motor during a full throttle run-up:

- The aerodynamic noise (coming from the rotating parts and air-cooling if so) and the mechanical noise are present at low frequencies at high speed.
- The electromagnetic noise results from magnetic forces generating deformations and vibrations in the stator and the motor housing, which produce noise according to the radiation efficiency. This noise is twofold:

- Harmonic tones with speed-dependent frequencies at main motor orders, resulting from magnetic pole/slot interactions between rotor and stator, exciting the stator (resp. rotor depending on motor type), possibly strengthened when meeting structure spatial modes. The motor design plays a significant role in their characteristics.
- Multiple tones arranged in V-shape on both sides of switching frequency values, resulting from pulse width modulation (PWM) harmonics of the current supplied to the motor. They occur in a frequency range where no other source contribution generally occurs. If located at quite high frequencies, their audible impact may be limited due to human ear sensitivity as well as because they remain distant from the frequency range of structure resonances.

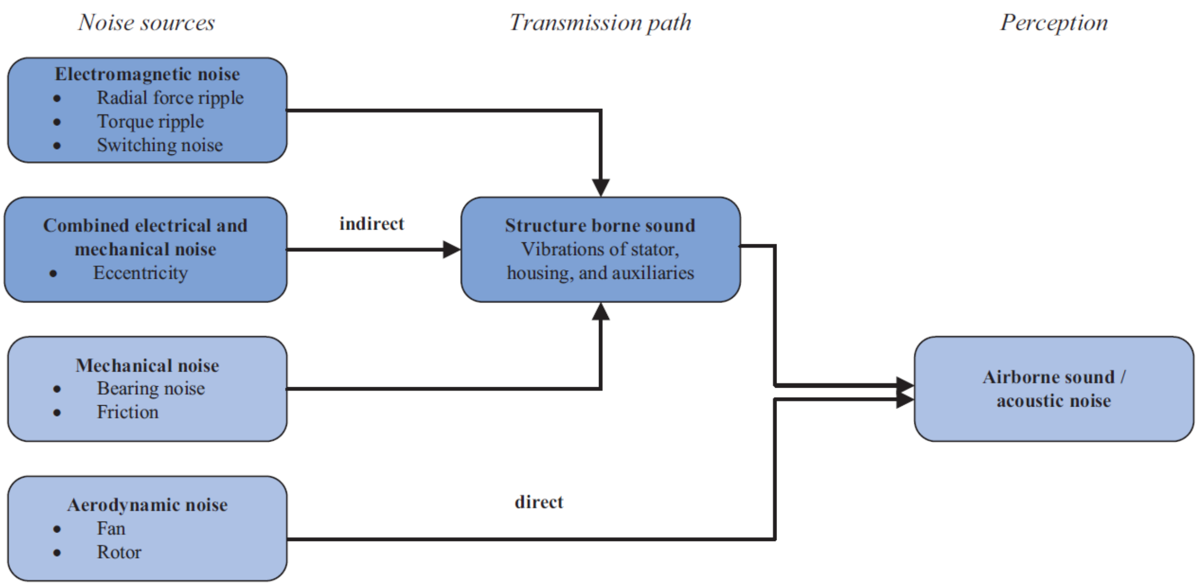


Figure 4-3 Noise sources in an electrical machine (from [46]).

At low speed, PWM tones dominate whereas both pole/slot interaction and PWM tones contribute at medium speeds. They emphasize during acceleration and deceleration phases. The switching frequency is constant in most EVs, generally lying between 5 and 20 kHz, but the modulation harmonics on both sides are speed-dependent (Figure 4-4). It should also be noted that, for the same torque, the noise from an electric motor in regenerating mode may differ from those emitted in driving mode. Electric motor noise mitigation involves acting on motor design (dimensions, number and shape of the slots, air gap), switching frequency and PWM strategy.

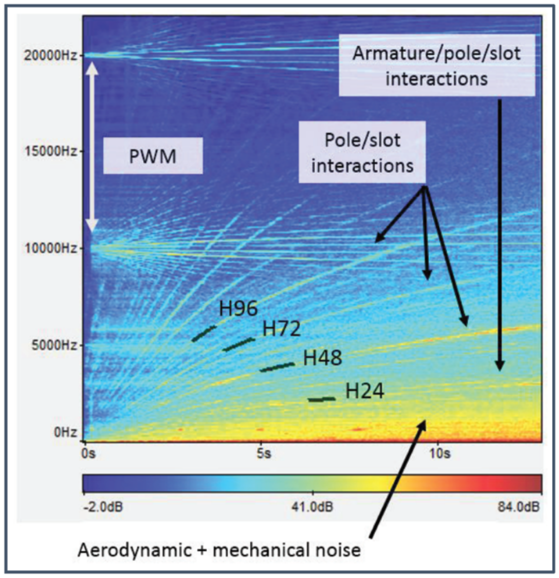


Figure 4-4 Sound pressure level measured close to an electric motor during a run-up from 0 to 110 km/h at maximum torque (from [44]).

4.1.1.2 Motor noise inside the vehicle cabin

Motor noise concern has raised most attention considering the driver and passenger acoustical comfort and their perception of the sound quality. In complement to the motor vibration/noise emission, this takes account of the vibration and noise transfer paths through the vehicle structure from the motor compartment to the cabin interior. It turns out that motor noise may be more annoying by its frequency content, in particular high frequency tones, than by its actual sound level. Studies mainly use psychoacoustics approaches for the interior noise assessment and sound quality improvement, with a focus on tonalities perception through dedicated indicators [45], [48]–[50]. The topic of noise perception of electric vehicles is specifically studied and detailed in section 5 of the present deliverable.

4.1.1.3 Motor noise outside the vehicle

The contribution of the motor to the outside noise radiated by a driving EV in real conditions is not precisely known. Indeed, it cannot easily be separated from the other sources, in particular the rolling noise which has a significant part in the overall noise. Sooner, states of the art on EV exterior noise emission have been published in two separate projects [51], [52] conducted over the period 2013-2015, respectively COMPETT (part of the ERA-NET-TRANSPORT program ELECTROMOBILITY+) and FOREVER (linked to the CEDR Transnational Research Programme). The present overview gathers literature results by grouping them according to three possible proceeding approaches for assessing EV propulsion noise in real rolling conditions. Since EV field is a quite evolving area of technology, it preferably focuses on studies conducted this decade for a better representation of current vehicle trends.

On-board nearfield measurement

A few studies have considered the contribution of propulsion noise from measurements recorded on an on-board microphone located near the motor under the hood. A first approach used measurements carried out in a similar way on both a conventional and an electric vehicle. The propulsion noise was recorded on the on-board microphone together with the driving speed along a route. Then, the noise level difference between the two vehicle types was evaluated within speed classes (for instance by 5 km/h steps) over the whole speed range. Next, the assessment of on-board propulsion noise reduction between the two vehicles was identically transferred to far-field noise levels. By using existing knowledge of conventional vehicle propulsion noise in the far-field, for example the one given by a noise emission model like the European prediction model CNOSSOS-EU, the propulsion noise of the electric car was thus estimated. This processing has been applied in [53] on a VW Passat and a Toyota Prius. In this case, hybrid and electric operating modes do not seem to have been distinguished and the noise reduction by the hybrid drivetrain was assessed to be 15 dB at idle decreasing with increasing speed until cancelling at 60 km/h. Frequency distribution was not provided. This approach assumes on one hand that the on-board microphone records only propulsion noise (no contamination by aerodynamic or rolling noise) and on the other hand that the near-field/far-field transfer function is identical on both vehicles.

Another study used on-board microphones, firstly in the motor compartment for propulsion noise, secondly near one tyre for rolling noise [54]. In the context of this paragraph, we focus on the first one. Equivalent levels on 1s duration were recorded along a given route while driving conditions (motor speed and load, vehicle speed) were taken from the CAN bus and a GPS system, with a hybrid vehicle (Toyota Prius) and an electric one (Nissan Leaf). The overall equivalent level and the mean spectrum over the whole route duration were calculated, then averaged on several runs of the same route. Thus, this integrated all the speed range and driving conditions met on the way. Then, the attenuation between the near-field microphone and the far-field point considered had to be estimated in order to infer the far-field noise source contribution at the reception point. This was achieved in two steps. First, the attenuation by the car body was determined experimentally with a speaker. Next, the attenuation due to the propagation, taking account of the ground effect, was calculated. Both attenuations were combined to the previously integrated on-board equivalent level and spectrum to assess far-field propulsion noise characteristics. However, these characteristics are specific to the selected route and scenario, mixing the speed-dependent noise spectrum and overall level according to the whole speed/acceleration/deceleration distribution encountered. As such, it does not inform on the speed dependent propulsion noise properties.

On-board microphones were also implemented in the European project CityHush. A simulation tool was developed for the binaural auralisation of vehicle pass-by noise, combining tyre/road noise and driveline noise. A wide measurement campaign involving on-board sensors, trackside microphones, artificial head and microphone array (see also further in this section) had been carried out to finalise and adjust the tool. It has also been applied to separate roadside contribution of the two individual noise sources of EVs, relying on on-board microphones [55]. Concerning the driveline, one microphone was located in the motor compartment, another being at the backside of the vehicle behind the motor compartment. Other microphones targeted the rolling noise. Source noise signal at the reference trackside position distant of 7.5 m from the track centre (height 1.2 m) was calculated with the synthesis tool to get the source contribution to the overall pass-by signal. This took account of radiation filters of:

- the transfer path through the engine compartment/hood, using the two on-board microphones;
- the sound propagation, including attenuation due to distance and frequency shift due to Doppler.

The radiation directivity of the source was disregarded. Lower quality of the driveline estimate was expected in case of a strong rolling noise contribution due to a more challenging model adjustment. It was also suspected that the on-board microphones might partially include some rolling noise. Results of global near-field and far-field noise levels with a Mitsubishi iMIEV at constant speed are illustrated in Figure 4-5. They may be compared to the results of Figure 4-7 (except for a possible difference in road surface), since Mitsubishi iMiEV and Citroën

C-Zero are a single EV model under different brands. The report does not provide frequency information and spectra. A Fiat 500 EV has also been tested similarly.

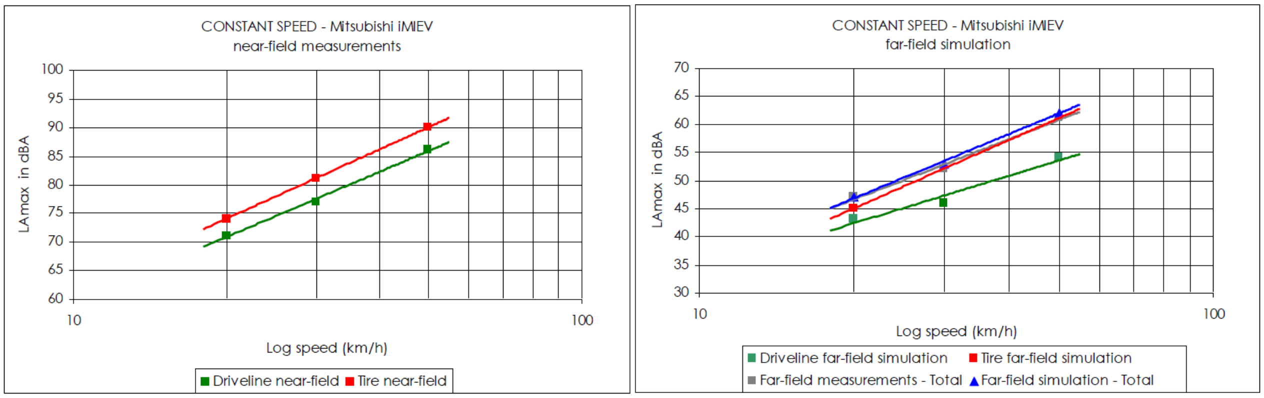


Figure 4-5 Near-field (left) and estimated far-field (right) sound pressure levels of the noise source contributions for a Mitsubishi iMiEV at constant speed – Driveline noise in green (from [55]).

The simulation results seem to provide quite correct overall estimates. This relies on a rather heavy tool development and experimental work, which might require updating for each different vehicle.

Pass-by measurement

The approach to the contribution of EV propulsion noise has mostly been achieved at vehicle pass-by, using a roadside microphone according to CPB (SPB) standard procedures, sometimes with an artificial head if psychoacoustical perspectives are targeted. However, the extraction of propulsion noise from the rolling noise when mixed within the overall noise is challenging. Neither can rolling noise be considered alone for comparison in real driving conditions due to the inability to disengage the electric motor.

The point of view quite often adopted consists in comparing noise emission from an EV and a conventional vehicle, similar to each other as far as possible. However, most of the time this cannot be carried out all things being equal, as other parameters can change in addition (tyre type or dimensions, vehicle model and car body). This impairs the extraction of the relative change of propulsion contribution only. Information on the overall noise reduction has generally been seen as sufficient in studies: the overall global noise levels and spectra are directly compared, according to speed and driving conditions. In particular, it was used in many detectability studies raising safety issues for visually impaired persons and other vulnerable road users. Since beyond the scope of LIFE E-VIA project, these studies are not reported here. Several projects oriented toward environmental noise concern have also used the same principle, among which [55] and [56].

The COMPETT project, part of the ELECTOMOBILITY+ programme of ERA-NET-TRANSPORT, was focused on noise emission from electric passenger cars. It included an experimental comparison of electric and conventional vehicles, the final purpose concerning the impact of introducing electric vehicles in the traffic on environmental noise in urban areas [56]. It consisted in controlled pass-by (CPB) measurement in various common urban driving conditions: constant speed from 10 to 60 km/h, acceleration with different rates from 10 to 40 km/h initial speed, deceleration (without friction brake) from 20 to 60 km/h initial speed, with two pairs of equivalent conventional/electric vehicles:

- an ICE Citroën Berlingo and an electric Citroën Berlingo, with identical car bodies but different tyres;
- a VW Golf Variant and a Nissan Leaf, with identical tyres in model and dimension.

Thus, in each pair, the propulsion mode was not the only varying parameter and overall noise level differences observed cannot certainly be assigned solely to the driveline technology. No information is given on the background noise level and spectrum, but the surroundings seem rather quiet. The Citroën Berlingo EV is 5 dB(A) quieter at 10 km/h than the ICE one but the difference cancels from 30 km/h and the EV model becomes even noisier by approximately 2 dB(A) at 40 km/h. At all speeds, the ICE Berlingo exhibits strong low frequency components, which is classical for a conventional vehicle. These are inexistent on the electric model, which also offers a lower contribution over 400 Hz. No high frequency component may be noticed in the electric version. The same spectral behaviour occurs also for the second vehicle pair. Despite identical tyre models, the global noise level of the Nissan Leaf is lower at all speeds, even when rolling noise is expected to dominate. This points out that level differences cannot be explained solely by the change of driveline type. Another factor is likely to be involved and prevents definitive conclusions on driveline noise contribution. Vehicle type ranking remains the same in all driving conditions, with variable differences. In unsteady driving condition, there is a trend to an increase of the Leaf spectra in the third-octave 10 kHz. This could be due to PWM around the switching frequency of the electric motor near this frequency. Spectrogram would have been useful for confirmation.

This illustrates the difficulty to extract the differences in driveline contribution by a comparison between two vehicles. Another approach consists in taking advantage of the higher speeds to estimate rolling noise and, by extrapolation towards lower speeds, to calculate the driveline contribution by a subtraction from the overall noise, as presented below.

The European project CityHush defined noise criteria to allow vehicles to enter quiet zones of the cities [55]. During project activities, a series of constant speed (cruise-by) and acceleration (wide-open-throttle WOT) pass-by runs, derived from standard ISO 362:2007[4], were performed with several EVs:

- cruise-by at 15, 20, 25, 40, 50 km/h
- WOT with initial speeds 20, 30 or 50 km/h (and hence higher speed values at the time of maximum noise level)

The driveline and rolling noise separation procedure from the total cruise-by noise involved several steps and assumptions:

- Rolling noise follows expression $m \ \log v + c$, where m and c are constant parameters for each car and v is the speed. m and c are determined by fitting this model to A-weighted peak level values measured at the highest speed measurements (the speed range was not documented).
- Driveline noise follows a similar expression $m' \log v + c'$, where m' and c' are constant parameters specific to each car. m' and c' are calculated by fitting the model (rolling noise $\oplus$ driveline noise) to all cruise-by peak values, $\oplus$ meaning energetic summation.

There is some uncertainty on the procedure implemented in WOT conditions, due to seeming inconsistency between text and figures. Referring to the former, WOT driveline noise is estimated similarly to cruise-by second step, but assuming the WOT rolling noise to be $m \ \log v + c + 2 \ dB(A)$. The latter suggests that the driveline noise is a constant while the rolling noise increases linearly with $\log v$ and new parameters.

For the C-Zero, the speed of intersect between both components is close to 10 km/h. Velocity slope in the 200-400 Hz range suggests the main contribution of the driveline, while it meets rolling noise slope in the range 800-

[4] Previous version of the standard updated in the meantime as ISO 362-1:2015.

1250 Hz (Figure 4-6). Separate driveline spectra are not provided. WOT result gives a driveline noise higher than rolling noise up to 50 km/h.

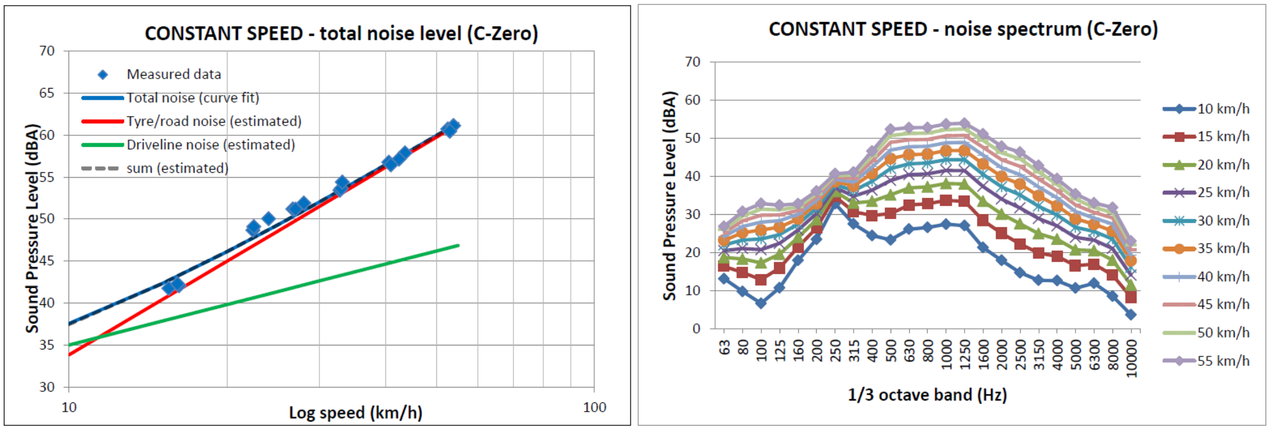


Figure 4-6 Driveline noise estimation in the global cruise-by noise (left) and overall spectra (right) for a C-Zero in the CityHush project (from [55]).

A similar approach for separating the two main noise source contributions and assessing the EV propulsion noise has recently been proposed in a study for DEFRA (UK) [57]. The study focuses on the separation method, it does not provide source contribution values at this stage. This is described later in section 6.1.1 on noise prediction.

Microphone array measurements

A microphone array is a multiple sensor device, allowing noise source separation on a vehicle at pass-by due to its steerable directivity. This is a rather complex equipment compared to standard microphone processing, now well tried with beamforming algorithm in various transportation areas. The separation of sources is carried out according to their spatial distribution. It also avoids a large part of the disturbance due to background noise. In the European CityHush project, an array composed of 192 microphones has been used for detecting, locating and ranking the dominant noise sources on several vehicles, including an electric Fiat 500 and a Citroën C-Zero, in various driving conditions [58]. The main purpose was the identification of the main noise sources for the development of a vehicle noise simulation tool in order to derive indicators useful in psychoacoustic studies. A detailed experimental work has been carried out. However, only a few noise source maps illustrate the report and the results on noise source assessment are not provided. An interesting complementary investigation has been made on the Citroën C-Zero, testing the transfer function and horizontal directivity for the motor noise. This highlights the sideways and backwards propulsion directivity of this vehicle where the motor is located near the rear axle.

The FOREVER project implemented a 57-microphone array to investigate vehicle noise sources at constant speed, in acceleration, deceleration (regenerative braking) and frictional braking [52]. This was applied to a hybrid vehicle. When in electric mode, the separation of the front axle area (rolling noise only) and the rear axle (rolling noise + electric motor noise) pointed out a slightly different behaviour (Figure 4-7, green and red curves in the figure on the right). The global noise difference, attributed to electric propulsion noise, was evaluated to 1-2 dB(A) at low speed. Although a frequency analysis was achieved in octave bands, the difference due to propulsion noise was not included in the report. A Citroën C-Zero was also tested in the project, but no microphone array measurement was carried out on this EV.

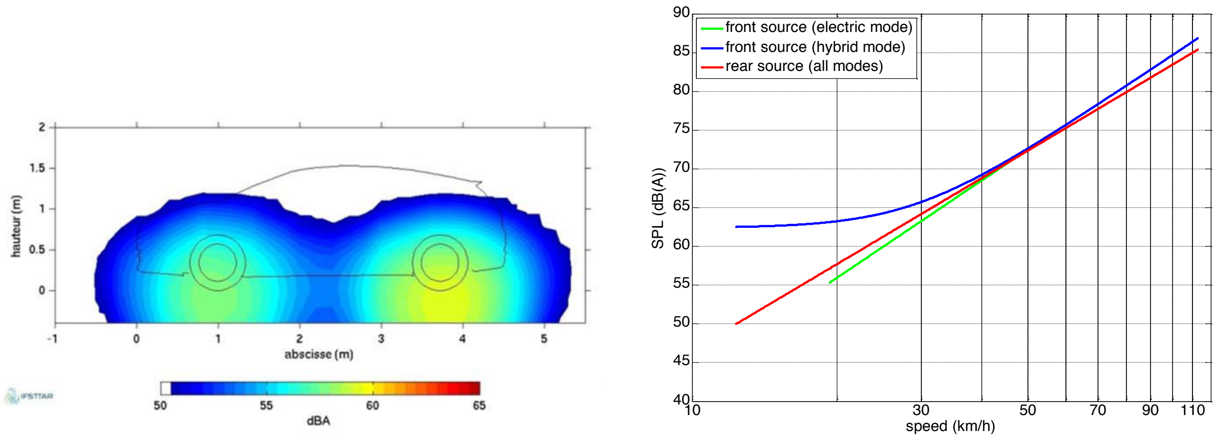


Figure 4-7 Left: Noise map of an hybrid car at steady speed 23 km/h in electric mode – Right: average contribution of the front and rear axle areas at constant speed, SPL at 2.7 m – FOREVER project [52].

It should be noted that microphone array techniques are generally relevant on a narrower frequency range than the one advised in pass-by vehicle noise standards. In FOREVER, it was restricted below octave 4000 Hz. The source separation performance reduces towards low frequencies.

Synthesis

At the present stage, no precise quantitative knowledge of the exterior noise emission from the electric motor/propulsion in real driving conditions was found in the literature. Although the potential for reduction relatively to conventional vehicles is proved, the exact contribution of driveline differences is hard to estimate from vehicle comparisons since other parameters often change simultaneously. Nonetheless, low frequency components of conventional vehicles are removed on EVs. High frequency components, possibly linked to the switching frequency and the PWM in the current supplied to the electric motor, may come out under heavy motor loads.

Approaches involving on-board sensors provide an interesting solution for noise source separation but require a good knowledge of the transfer functions from the near-field to the far-field. Correct adjustments may be resource intensive.

The energetic subtraction approach of the speed-dependent rolling noise contribution from the overall pass-by noise to separate driveline noise relies on the application of a correct model. The approach is simple to implement but there is a risk of amplifying the uncertainty towards the driveline estimate. In frequency analysis, the linear speed-increase commonly used for rolling noise may be inappropriate in some frequency bands, particularly in case of narrowband components of speed-dependent frequency.

Noise source separation with microphone arrays provides a correct spatial separation, requiring substantial experimental and processing resources. The efficient frequency range does not cover the entire range generally considered in environmental noise, with limitations towards lowest and highest frequencies.

4.1.2 Rolling noise

Rolling noise, commonly denominated by tyre/road noise, is the main source of road noise emission under fluid traffic conditions. Since the last decades, tyre/road noise has been predominating over the engine noise of ICEV from the third gearbox ratio, corresponding to a rolling speed of 50 km/h for an ICEV fleet of the early 2000s

[59], and falling below 30 km/h for a more recent ICEV fleet [60]. For electric vehicles with a rather low propulsion noise, tyre/road noise predominates from about 20 km/h at steady speed [60], [61].

The tyre/road noise is a broadband noise whose spectral energy is mainly contained between 300 Hz and 5000 Hz, with a maximum of energy generally located between 700 Hz and 2000 Hz. Tyre/road noise is the result of complex interaction mechanisms between the tyre and the road surface during rolling [62], which generate noise sources of mechanical origin (vibratory excitation of the tyre) and aerodynamical origin (air-pumping and resonance of cavities). These sources are then amplified by the horn-like geometry formed by the tyre and the road (the so-called "horn effect"), before propagating in the environment. For a more detailed description of the mechanisms generating tyre/road noise, the reader can refer to the reference book of Sandberg and Esjmont [63]. The mechanisms involved in tyre/road noise affect different frequency domains of the noise spectrum. The sound energy resulting from each mechanism is also influenced by the speed of the vehicle. From the literature, Kuijpers and van Blokland [64] have given an overview of the frequency region and the speed exponent for each mechanism. On the one hand, radial vibrations of the tyre are dominating noise generation at low frequencies (below 1000 Hz). On the other hand, noise at higher frequencies (above 1000 Hz) is generated by different types of mechanisms, such as tangential vibrations of tread blocks, adhesion and stick/slip phenomena and air-pumping. At the present time, the respective contribution of each of these high-frequency mechanisms remains poorly understood.

Tyre/road noise is greatly influenced by road surface properties (texture, absorption and mechanical impedance) and by the characteristics of the tyre (tread pattern, width and radius, structural design and material compounds). A significant noise reduction can be obtained by a proper combination of the tyre and the road surface. For the sake of illustration, a recent study based on 12 different road surfaces and 16 different tyre models (including EV tyre models) have shown a potential noise reduction of about 9 dB(A) between the quietest and loudest road surfaces, while a potential noise reduction of up to 4 dB(A) can be obtained using tyre with optimised acoustic properties. In the following, the main relevant studies on tyre/road noise within projects dedicated to EVs are summarised.

QCITY project (2005-2009): During the QCITY project, a concept of low noise urban area was proposed. This kind of environmental zones only allows low noise electric vehicles such as EVs in combination with solutions to reduce tyre/road noise, e.g. reducing the road surface roughness and Nominal Maximum Aggregate Size (NMAS) and fitting the vehicles with the 20% quietest tyres. Therefore, a study was performed to assess the potential noise reduction of five different tyre models selected from the 20% most quiet tyres on the market, rolling on a smooth dense asphalt concrete with NMAS of 8 mm [65]. These tyres were not specifically designed for EVs. The aim was to reflect the noise reduction potential by limiting the study to the tyre tread designs and limiting the influence of the road surface roughness. Figure 4-8 gives the five tyre models considered for noise measurements in [65]. Noise was measured at constant speed between 40 km/h and 70 km/h using a single wheel CPX trailer. The test section was 300 m long and the road surface was a thin asphalt layer VIACOGRIP 8, i.e. a smooth surface of NMAS 8.

Figure 4-8 Five tyre models of dimensions 225/45 R17 used for CPX noise measurements in [65].

The results have shown that the noise reduction potential of the tested tyre was 1.7 to 2.1 dB(A), respectively at 40 km/h and 50 km/h, when running on the smooth road surface. The noise reduction potential was calculated as the arithmetic average of all tested tyres minus the sound level for the quietest tyre, which turned out to be the Goodyear Eagle Vector tyre model. This tyre model also had the lowest rubber hardness value (60 Shore A). Figure 4-9 gives the acoustical ranking of the tyre at typical urban driving conditions (30 to 50 km/h) and country road driving conditions (50 to 90 km/h). Tyre ranking is changing with the speed range due to different values of the speed exponent, varying from 2.86 for the Michelin Primacy HP tyre model to 4.25 for the Goodyear Excellence tyre model.

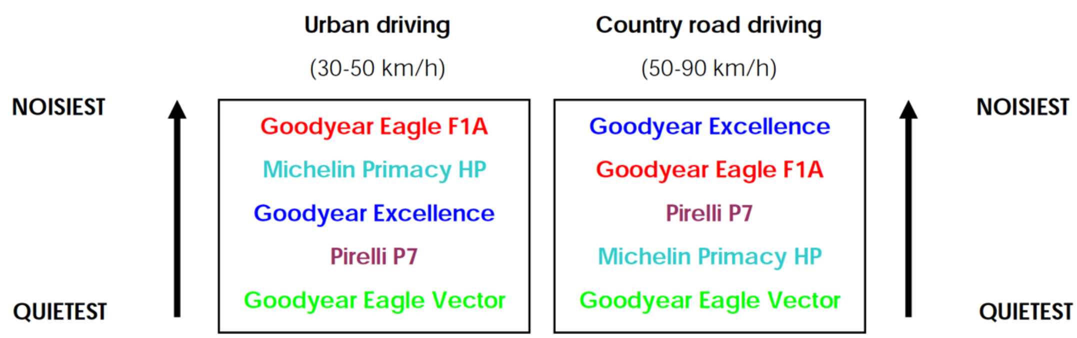


Figure 4-9 Acoustical ranking of tyres at typical urban and country road driving conditions in [65].

It was concluded in [65] that the results could be used to prescribe low noise tyres with silent tread patterns when rolling on smooth road surfaces. In fact, it was estimated that reducing NMAS of a dense road surface from 16 mm to 6 mm would at least lead to a noise reduction of 3 dB(A). Combining this action with EVs fitted with 20 % of the quietest tyre would give at least an additional reduction of 2 dB(A), resulting in a total tyre/road noise reduction of 5 dB(A).

Within the QCITY project, another study was performed to assess the noise reduction from hybrid vehicles in comparison with standard gasoline powered passenger cars [66]. The aim was to obtain primary results for requirements on tyre/road noise level in the concept of quiet urban area. Therefore, driveline noise for a hybrid electric vehicle (Toyota Prius model from 2006) and a standard gasoline car (Volvo V70) has been estimated. The hybrid car was propelled by a gasoline engine and/or an electric motor. The results indicated that the driveline noise for the hybrid vehicle was reduced by 12 dB(A) in comparison to the gasoline car. A clear peak at 250 Hz was obtained for the hybrid vehicle due to the electric motor. The results showed that the limit velocity over which tyre/road noise is dominating was 13 km/h for the hybrid vehicle in electric mode and about 30 km/h for the gasoline car. As shown in Figure 4-10, it was finally concluded that a total noise reduction of 11-12 dB(A) at all vehicle speeds for the hybrid vehicle compared to the gasoline car requires a tyre/road noise reduction of 10 dB(A), with the assumption that vehicles are fitted with the same type of tyres running on the same type of road surface.

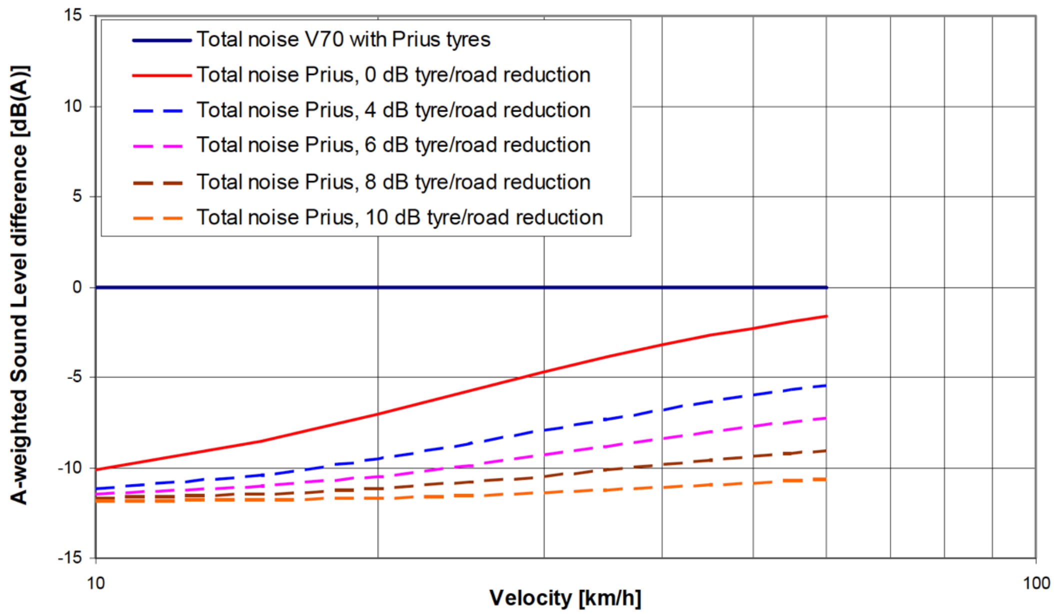


Figure 4-10 Total noise difference between hybrid (Toyota Prius) and gasoline (Volvo V70) passenger cars for different values of tyre/road noise reduction [66].

A new concept of low noise tyre, the Twin-tyre concept, was also developed during QCITY [67]. The main idea was to use this new concept of tyre in combination with EV in order to reduce tyre/road noise in urban area. As can be seen in Figure 4-11, the Twin-tyre concept consists of two narrow tyres with small crown radius mounted on the same rim with a lateral separation between them. This spatial separation limits the acoustical interaction between both tyres, which significantly reduces the horn amplification. The influence of the distance between the two narrow tyres on the horn effect was modelled and experimentally assessed during the QCITY project [67]. Figure 4-12 shows that the noise reduction as a function of tyre spacing reaches a plateau when the distance between tyres is above 50 mm, corresponding to a total width of the Twin-tyre of 245 mm. It was concluded that this total tyre width is commercially realistic to achieve.

Figure 4-11 The concept of Twin-tyre (left) and Twin-tyre mock-up developed during the QCITY project [67].

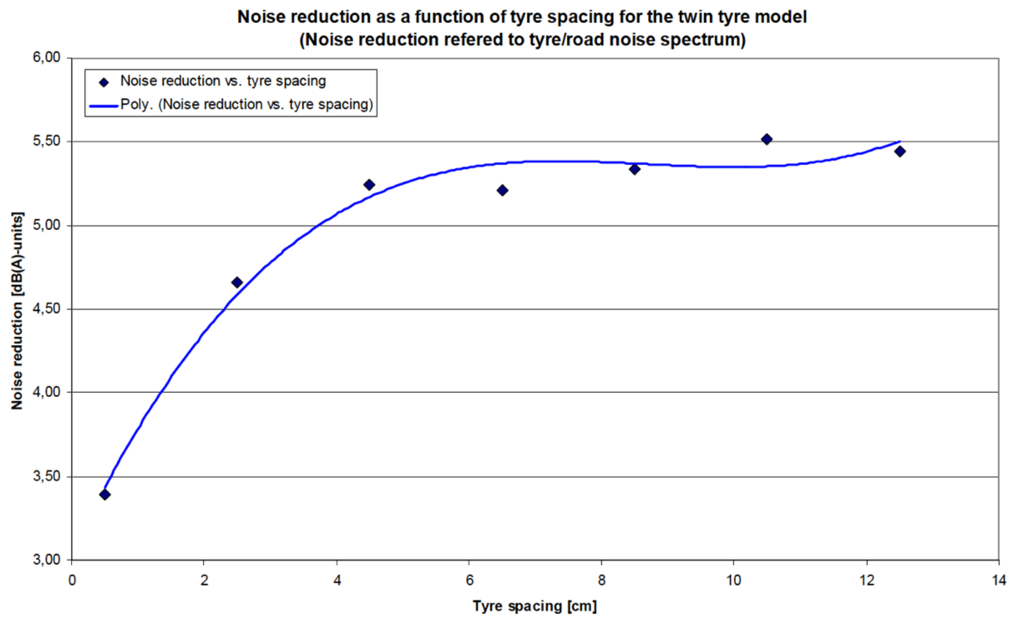


Figure 4-12 Noise reduction as a function of spacing between narrow tyres of the Twin-tyre mock-up [67].

Based on the concept of Twin-tyre and preliminary results of [67], a so-called DualQ prototype of Twin-tyre was developed and evaluated by means of a single wheel CPX trailer during the QCITY project [68]. A special rim was built in order to fit two motorcycle tyres (Dunlop 90/90-19 52H) which were selected due to the suitable width of 90 mm, the small crown radius and the outer diameter comparable to normal passenger car tyres (Figure 4-13). Two kinds of DualQ prototypes have been considered during the CPX tests, the first with tyre spacing of 45 mm (DualQ 1) and the second with tyre spacing of 60 mm (DualQ 2). Both tyres had a rubber strip of thickness 8.6 mm glued on to the inner side of the tyres in order to reduce their vibrations. The test sections were a rough asphalt pavement SMA16 and a smooth asphalt pavement VIACOGRIP8. The reference tyres selected for comparisons were Goodyear Hydragrip tyres with dimensions 205/65R15 and 215/65R15. On the SMA16, the DualQ 2 prototype reduces tyre/road noise by 8 dB(A) in comparison with the reference tyre, at speeds between 60 km/h and 80 km/h. As shown in Figure 4-14, on the VIACOGRIP8 test section, a reduction of 6.3 dB(A) at speeds between 40 km/h and 60 km/h was observed for both DualQ prototypes in comparison with the reference tyres. Thus, it was concluded that the DualQ concept was proved successful and could give a substantial reduction of tyre/road noise, especially when combined with EVs.

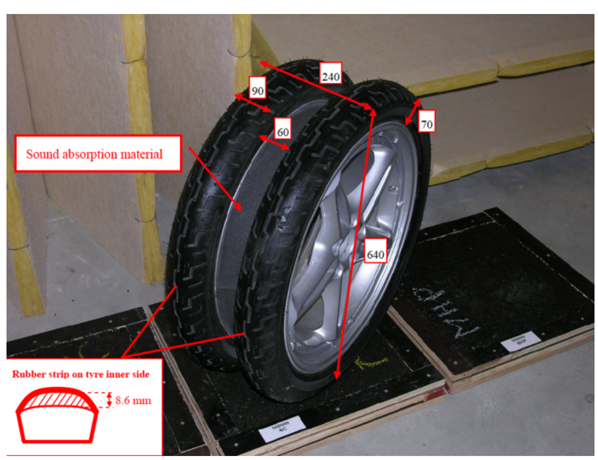


Figure 4-13 Prototype of low noise DualQ tyre developed and evaluated during the QCITY project [68] .

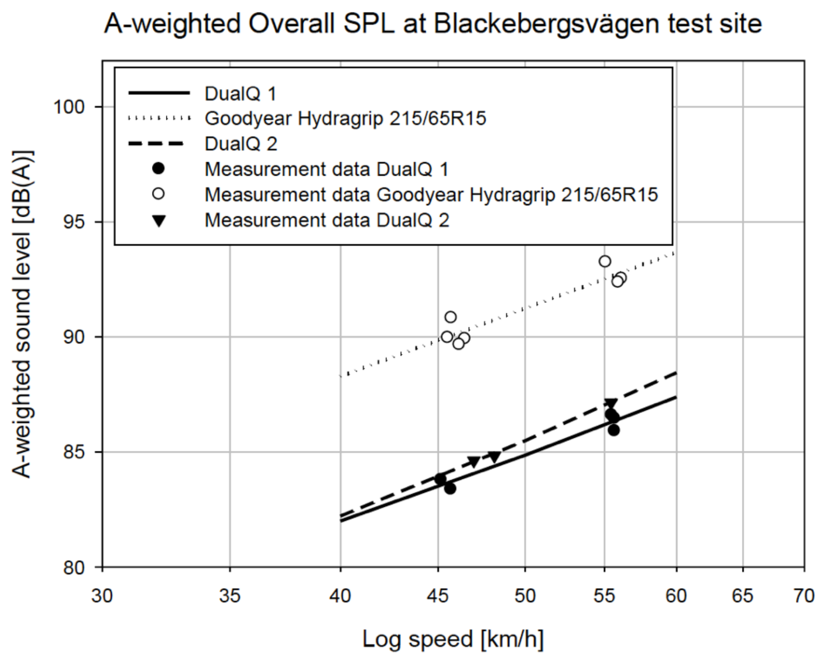


Figure 4-14 CPX noise levels measured on the VIACOGRIP8 test section for DualQ 1 and DualQ 2 prototype tyres and for the reference Goodyear Hydragrip tyre during the QCITY project [68].

CityHush project (2010-2012): The European project CityHush (2010-2012) dealt with Acoustically Green Road Vehicles and City Areas, with the aim of providing city administrations with solutions and tools for reducing noise in urban area. Acoustically green vehicles were a main item of the project and several tasks involved investigations and measurement with electric or hybrid vehicles.

In Work Package 3, a study was performed in order to define noise criteria for vehicles to access quiet zones in urban area, labelled as Q-zones. Functional noise specifications for purchasing green low noise vehicles were investigated in [69], while noise criteria for vehicles to enter Q-Zones were reported in [55]. Both [69] and [55] are based on two noise measurement campaigns on hybrid and electric vehicles described in Appendix 1 and 2 of [55]. The first experimental campaign (Appendix A) was performed by Acoustics Control. Pass-by noise emission of four electric vehicles and one hybrid vehicle have been performed according to new ECE R51 method based on ISO 362-1:2007 standard. The aim was to derive the driveline noise and rolling noise components for each vehicle. The four electric vehicles were a Mitsubishi iMiEV, a Fiat 500 EVadapt, a Peugeot iOn and a Citroen C-Zero (Figure 4-15). It should be noted that Mitsubishi iMiEV, the Peugeot iOn and the Citroën C-Zero are actually identical vehicles, resulting from a partnership between Mitsubishi and PSA Peugeot Citroën. They were fitted with the same tyre models Dunlop Enasave 2030 145/65 R15 at the front and 175/55 R15 at the rear. The Fiat 550 EVadapt was fitted with four identical Continental EcoContact 3 175/65 R14 tyres. The hybrid vehicle was a Toyota Prius fitted with Primacy Pilot 195/55 R16 tyres. This hybrid vehicle was driven in electric mode under 25 km/h. The road surface was a Dense Asphalt Concrete with a maximum aggregate size of 8 mm. No information was given on the background noise of the test site, which is mentioned to be a karting track.

Figure 4-15 Hybrid vehicle model and four electric vehicle models tested in [55] (Appendix A).

During the experiment, standard pass-by configurations were extended and included:

- constant rolling speed (crs) pass-by at 15, 20, 25, 40 and 50 km/h (cruise-by);
- wide-open-throttle (WOT) tests with initial speeds 20, 30 and 50 km/h (and hence higher speed values at the moment of the maximum noise level).

The following procedure has been used to separate driveline noise and rolling noise from the total noise at constant speed. The A-weighted maximum noise pressure level for the rolling noise, $L_{Amax,r}$, was firstly estimated from higher speed measurements, assuming the classical relationship $L_{Amax,r}$ = m log v + c, where m and c are constant parameters for each vehicle and v is the rolling speed. Then it was assumed that the $L_{Amax,d}$ for the driveline noise follows also the same expression $L_{Amax,d}$ = m' log v + c', where m' and c' are constant parameters specific to each car. This law should be appropriate for automatic or one gear transmission vehicles according to the author. Finally, the driveline noise was deduced by fitting the above law to the measured data, considering the total noise as the energetic sum of $L_{Amax,r}$ and $L_{Amax,d}$.

For WOT tests, the report specifies that the procedure is similar to crs tests, except that the rolling noise under acceleration is assumed to equal the constant speed rolling noise increased by 2 dB(A), due to a higher torque load onto the tyres in accelerating conditions. The procedure remains however unclear since it does not agree with the curves provided for each accelerating vehicle. From the figures in [55], it can be inferred that the authors suppose the driveline noise level vs. speed to be a constant and the rolling noise level to increase with log v.

As expected, the Mitsubishi i-MiEV, the Peugeot iOn and the Citroën C-Zero behaved quite similarly at constant speed and provided very close rolling noise components (Figure 4-16). They proved to be the quietest cars of the test whereas the Fiat 500 was the noisiest, the Prius being only slightly below. The difference between the quietest vehicle (Peugeot iOn) and the noisiest vehicle (Fiat 500 EVadapt) did not exceed 6 dB(A). It should be noticed that since the driveline component is comparatively small, its estimate could be somewhat inaccurate (see section 4.1.1.3).

Under acceleration the noise levels increase strongly compared with constant speed. The electric Fiat 500 EVadapt is the quietest at 20 km/h but the noisiest at 50 km/h. The authors point out that the driveline noise is dominant for every vehicle, except for the Fiat 500. However, one can wonder whether the assumption of a constant driveline noise component is appropriate, at least for this vehicle, and the component separation may be incomplete. Finally, due to rolling noise contribution at 50 km/h, it is recommended in [55] to perform WOT tests for electric vehicles type approval at a lower speed than 50 km/h, for instance 20 or 30 km/h, in order to favour driveline noise and hence to conform with the regulation intent through the acceleration test.

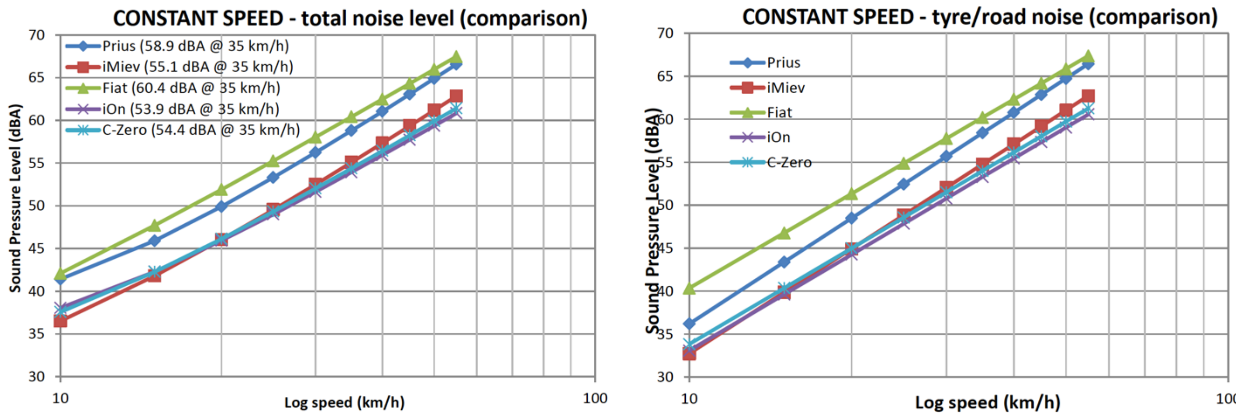


Figure 4-16 Comparison of overall pass-by noise levels for the different vehicles tested in [55]. Left: measured total noise level. Right: tyre/road noise level regressed from higher speeds.

A second set of experiments was performed by Head Acoustics and is reported in Appendix 2 of [55]. Two electric vehicles have been tested: a Mitsubishi iMiEV fitted with Dunlop Enasave tyres (of dimensions 145/65 R15 at the front and 175/55 R15 at the rear) and a Fiat 500 Liion (prototype of EV developed by Fiat) fitted with four Dunlop Duratech 175/75 R14 tyres. The test section was a small street in the country side and the road surface was smooth but the type and grading was not specified in the report. Measurements have been performed at non-standard pass-by positions, by means of an artificial head system located at 3 m from the vehicle at the closest point. Near-field noise was also recorded by means of four microphones respectively located at the front left tyre inlet, the front left tyre outlet, inside the engine compartment under the rear trunk and backside of the vehicle. This setup enables to separate the driveline noise and the tyre/road noise components at the pass-by position by means of a simulation tool, Traffic Noise Synthesizer (TNS) developed by the authors and fully described in [58]. Several pass-by noise measurements were carried out with respect to constant speed situations (20 km/h, 30 km/h and 50 km/h). Moreover, WOT pass-by scenarios were also considered, where the vehicle was accelerating. The vehicle was approaching at constant speed (20 km/h, 30 km/h and 50 km/h) and 10 m before the pass-by position at artificial head the vehicle accelerated with wide open throttle.

Figure 4-17 shows the results of the far-field simulation for the Mitsuhishi iMiEV for crs tests (left) and for WOT tests (right). At constant rolling speed (Figure 4-17, left), tyre/road noise is higher than driveline noise and the difference is increasing from 2 dB(A) to 7 dB(A) with rolling speed. On the contrary, in accelerating conditions (Figure 4-17, right), driveline noise is dominating tyre/road noise, particularly at lower (starting) speeds 20 and 30 km/h.

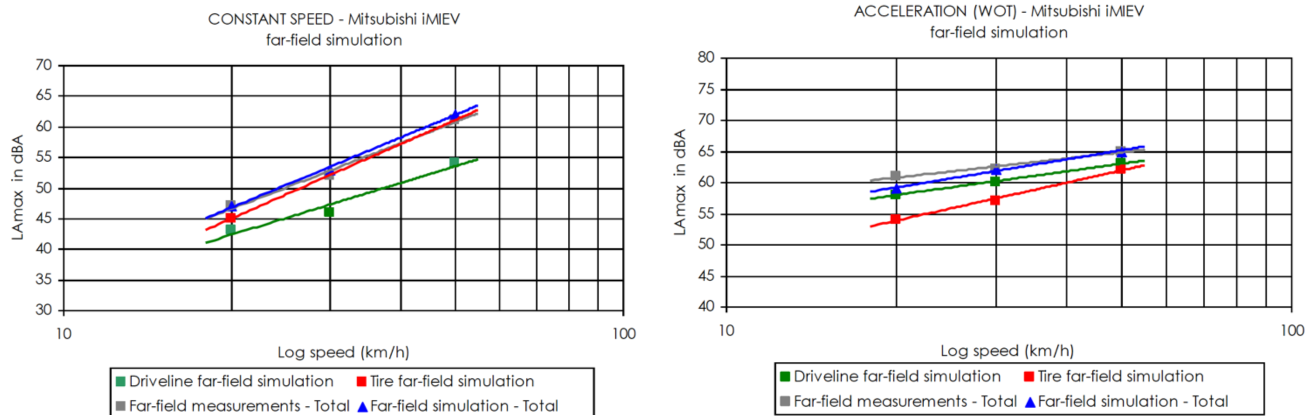


Figure 4-17 Overall simulated far-field noise levels for crs tests (left) and WOT tests (right) for the Mitsubishi iMiEV tested in Appendix 2 of [55].

In comparison to the Mitsubishi iMIEV the driveline noise contribution of the Fiat 500 Liion is lower, whereas the overall sound pressure levels are similar. At constant speed (Figure 4-18, left), tyre/road noise is by far dominating and is around 16 dB(A) higher than driveline noise. The same result is observed in acceleration condition, with tyre/road noise around 18 dB(A) higher than driveline noise. Thus, the authors concluded that this EV would greatly benefit from low noise tyres.

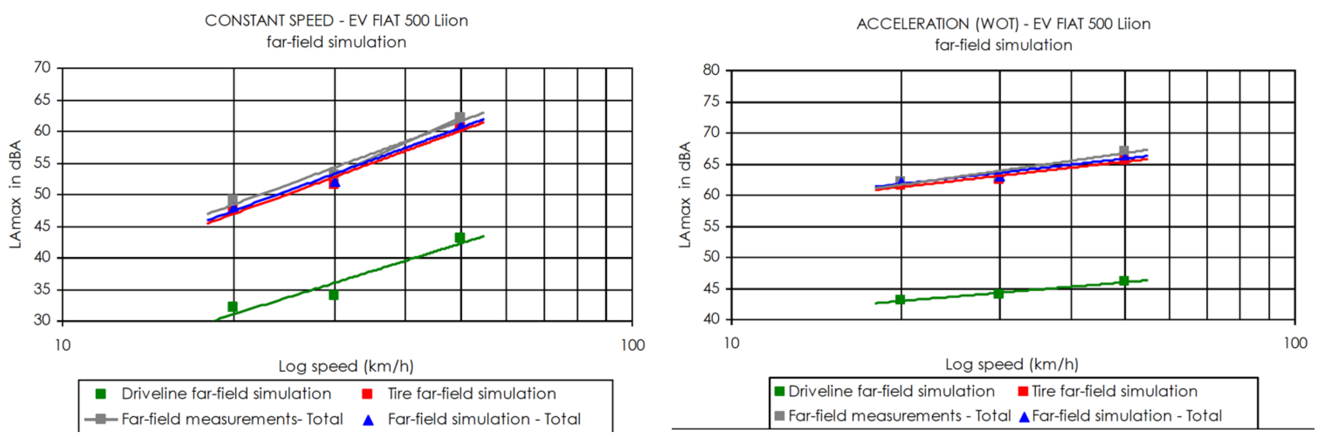


Figure 4-18 Overall simulated far-field noise levels for crs tests (left) and wot tests (right) for the Fiat 500 Liion tested in Appendix 2 of [55].

An important remark was pointed out by the authors in the conclusion of Appendix 2 of [55]: "*The low sound pressure levels of the driveline noise, especially regarding the driving condition constant speed, causes difficulties with respect to the estimations. As the tyre/road noise estimations differ only slightly from the measured total noise (less than 1 dB regarding the driving condition constant speed), the driveline noise contribution to the total noise is almost negligible. Calculating the driveline noise by subtracting the estimated tyre/road noise contribution from the total noise means that even a small uncertainty in the tyre/road sound pressure level estimation results in a great uncertainty of the estimated driveline sound pressure levels.*" This should be kept in mind during the LIFE E-VIA project.

Finally, several recommendations regarding noise criteria for vehicles to enter Q-zones have been formulated in [55]. It was suggested that a passenger car that is granted free access in Q-zones will have to fulfil $L_{Amax} < 64$ dB(A) (i.e. noise class A, cf. Figure 4-19) in real urban driving conditions, i.e. an average between crs and WOT noise levels at 50 km/h. This is about 8 to 10 dB(A) lower noise levels compared to normal passenger cars driving in urban area. This noise limit was likely to imply that only pure EVs will be granted free access in Q-zones. It was also mentioned that a reduction by 10 dB(A) at speeds above 50 km/h needs a reduction of tyre/road noise, e.g. by a selection of tyres with very quiet tread pattern running on a very smooth road surface with maximum aggregate size less than 5 mm.

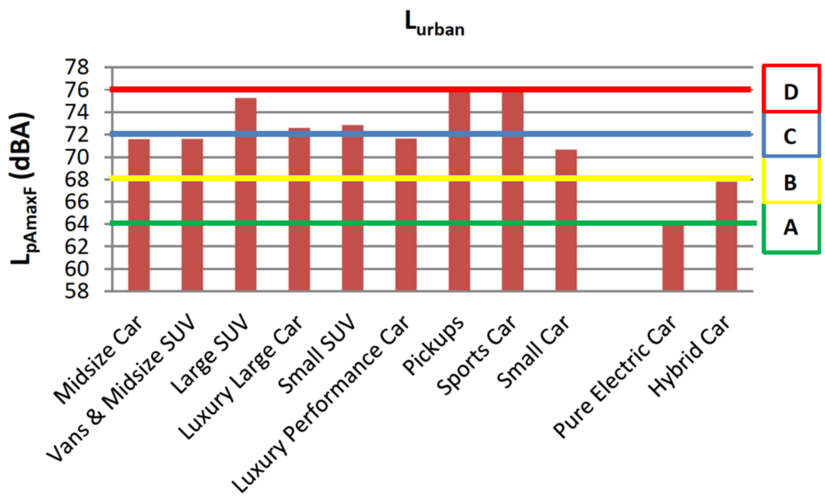


Figure 4-19 Upper limit of the four noise classes (A to D) suggested in [55] from measured and collected exterior noise data at 50 km/h.

Additional pass-by noise measurements have been performed by Head Acoustics and are reported in [58]. Various kinds of ICEV and EV were tested using different techniques: near-field and far-field measurements using monaural and binaural receivers as well as microphone array measurements. Different kinds of measurements have been performed on different proving ground and test tracks:

- comparison of an ICEV (gasoline Opel Vectra) and a hybrid vehicle (Toyota Prius);
- comparison of an ICEV Fiat 500c with an EV Fiat 500 Liion, equipped with identical tyres Dunlop Duratech 175/65 R14;
- comparison of standard and low noise tyres developed by Goodyear mounted on an EV Citroën C-Zero rolling on smooth and rough road surfaces.

From the first measurement campaign, it was found that the hybrid vehicle in electric mode is 6 dB(A) quieter than the ICEV with respect to the starting situation and is still 3 dB(A) quieter than the ICEV when driving at constant speed (30 km/h). In the second measurement campaign, different driving conditions have been considered: constant speed between 10 km/h and 50 km/h, full acceleration with starting speeds (10 m before the receivers) of 20, 30 and 50 km/h, coasting down test with starting speed between 10 km/h and 50 km/h and different acceleration conditions (low, mid and high). The main differences between EV and ICEV Fiat models are observed in constant speed and accelerating driving conditions. In constant speed driving conditions, at very low speed (10 km/h), the EV Fiat 500 Liion is about 10 dB(A) quieter than the ICEV Fiat 500c, while no difference in noise levels is observed at higher speed. This is due to tyre/road noise being dominant at higher speeds. In accelerating conditions, the EV is 10 dB(A) quieter than the ICEV at 20 and 30 km/h. In the last measurement campaign, the Citroën C-Zero was tested at constant speed (50 km/h and 80 km/h), in coast-down conditions from 50 km/h, 30 km/h and 20 km/h and in full load accelerating conditions from 30 km/h and 50 km/h. The results show that the rear low noise tyres are 3 dB(A) quieter than the rear standard tyres when rolling on the smooth surface at constant speed. For other configurations (front tyres, rough surface…) the noise levels between low noise and standard tyres are very similar. From all these measurements, it was firstly concluded that for an electric vehicle tyre/road noise is the main sound source for a speed of 30 km/h and above. Secondly, it was concluded that low noise tyres perform best on a smooth surface, and this combination should be preferred for the use in quiet zones in urban area.

During the CutyHush project, the work on the Twin-tyre concept was continued in order to assess its impact when mounted on EVs [70]. In [71], four prototypes of DualQ tyre (Figure 4-20), similar to the one tested during the QCITY project, were mounted on two vehicles, a Volvo C30 Pure Electric Vehicle (PEV) and a Volvo C30 T5 (gasoline). Reference car tyres (Continental SportContact2 205/50 R17) were also considered in the study. Pass-by noise measurements were performed at constant speeds between 50 km/h and 80 km/h on a very smooth dense asphalt concrete conforming ISO 10844.

Figure 4-20 Dimensions (in mm) of the DualQ tyre prototype (left) and DualQ tyre prototype mounted on the test vehicle during the CITYHUSH project (right) [71].

Figure 4-21 shows the pass-by noise spectra obtained for the Volvo C30 PEV (left) and the Volvo C30 T5 (right). A correction of the tonal noise due to tyre tread pitch of the DualQ prototype was performed by the authors in [71], in order to focus on the geometrical concept of the Twin-tyre. After applying this correction, the reduction of overall pass-by noise levels was 4.7 dB(A) for the EV and 4.1 dB(A) for the ICEV when fitted with DualQ tyres. While the concept of low noise DualQ tyre was validated, one should mention that the difference between EV and ICEV was quite small at 50 km/h, which is due to the domination of tyre/road noise at this vehicle speed. These results should also be considered with care since the effect of tread patterns on rolling noise was corrected for the DualQ prototypes in order to remove tonal noise.

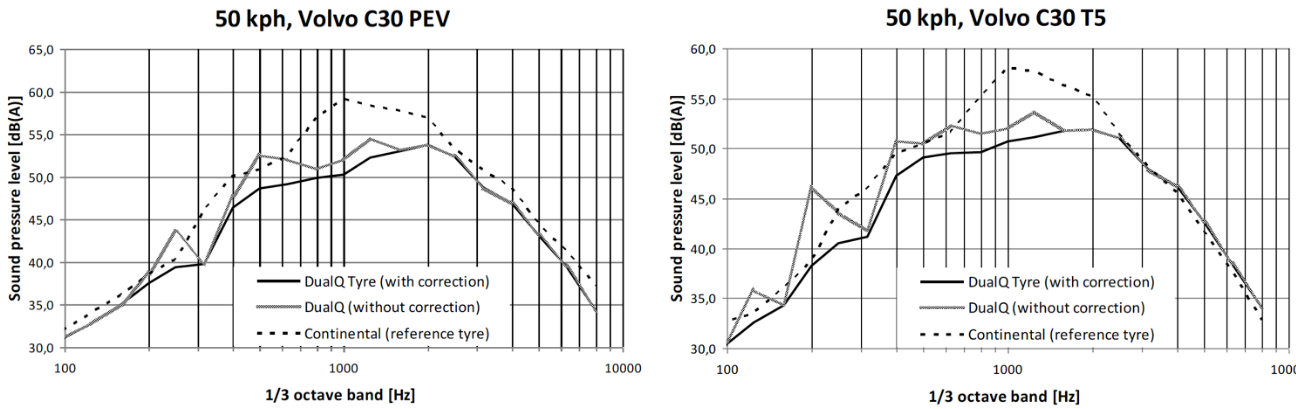


Figure 4-21 Comparison of 1/3 octave band pass-by noise levels for the DualQ tyre (with and without correction of tonal noise) with 1/3 octave band pass-by noise levels for the Continental reference tyres mounted on a Volvo C30 PEV (left) and a Volvo C30 T5 (right) in [71].

COMPETT project (2012-2015): Within the COMPETT project, a state-of-the-art literature survey was firstly proposed on noise from electric vehicles [51], [72]. One of the conclusions was that noise reductions found in existing studies could differ significantly depending on how the comparison between noise from ICEVs and EVs is achieved. However, at that time, most of the references found that the main noise reduction with EVs would be at low speeds, below 30 km/h to 50 km/h, due to the predominance of tyre/road noise above this speed range. The uncertainties related to the lack of information on tyres and pavement types used in the experimental studies was also pointed out in the literature review. Thus, tyres used on electric cars and the road surface they are rolling on should be carefully described in future studies, especially to predict noise reduction in urban area. It was also mentioned that driving conditions of EVs like acceleration, braking and backing should also be considered in the future studies.

During the COMPETT project, a noise measurement campaign was therefore carried out by the Danish Road Directorate in order to compare noise emission of EVs and equivalent ICEVs in urban driving conditions [73]. Four light duty vehicles have been considered for Controlled Pass-By (CPB) noise measurements: two Light Commercial Vehicles (EV vs. ICEV Citroën Berlingo) and two passenger cars of the same segment (EV Nissan Leaf vs. ICEV VW Golf). The tyres mounted on the different vehicles are given in Figure 4-22. While different on the two LCVs, the same tyre model (Michelin Energy Saver 205/55 R16) has been used on both passenger cars.

Citroën Berlingo EV	*Citroën Berlingo ICE*	*Nissan Leaf EV*	*VW Golf Variant ICE*
Michelin Agiglis 51 195/70 R15C 71 dB	Michelin Energy Saver 195/65 R15 G1 69 dB	Michelin Energy Saver 205/55 R16 70 dB	Michelin Energy Saver 205/55 R16 70 dB

Figure 4-22 Tyre model, size and noise level label for each vehicle tested in [73].

CPB noise tests have been performed in a large car park in an industrial area without disturbing traffic. The background noise was however not mentioned in the study. The road surface was less than 3 years old and was assumed to be a dense graded asphalt concrete with soft binder. Different urban driving situations have been considered during the tests, i.e. constant speed at 10, 20, 30, 40, 50 and 60 km/h, deceleration and acceleration. Overall CPB noise levels at constant speed are given in Figure 4-23 for both pairs of vehicles. For the Citroën Berlingo, it was observed that the EV was 2 dB noisier than the ICEV between 30 km/h and 60 km/h, and less noisy at low speeds below 30 km/h. This result was attributed to the higher label noise value of the tyres for the EV compared to the ICEV Citroën Berlingo. Considering passenger cars, at all speeds the EV Nissan Leaf emits less noise than the ICEV VW Golf. The noise level difference is about 4 dB(A) at 10 km/h and reduces to only 1.5 dB(A) at 60 km/h. Thus, the difference is becoming smaller when the speed increases. This was explained by the fact that tyre/road noise is becoming more dominant at higher speed. It was therefore concluded that for vehicle speed higher than 30 km/h, the choice of low noise tyres and quiet road surface is essential for noise reduction.

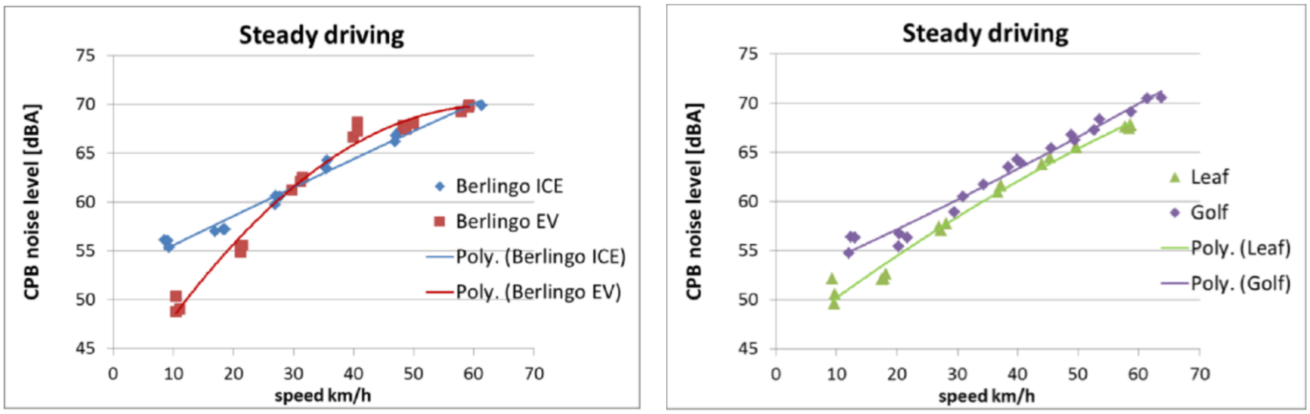


Figure 4-23 Overall CPB noise levels at steady speed for the EV and ICEV Citroën Berlingo (left) and for the EV Nissan Leaf and ICEV VW Golf (right) [73].

LEO project (2013-2016): During the LEO project, EV tyres have been tested on a wide range of road surfaces and compared with ICEV tyres. One of the main objectives of the project was to investigate the optimised combination of tyre and road surface, which could reduce the overall road traffic noise in urban area in the context of growing electrification of vehicles. Tyre/road noise measurements have been performed in Norway and in Poland using different methods, i.e. the CPX method (with a trailer or embarked on a vehicle), the CPB method and measurements on the laboratory drum facilities of TUG in Poland.

Results of laboratory experiments with the drum facilities of TUG have been presented in [74] and [75]. In [74], two models of tyres specifically designed for EVs have been compared with 15 models of ICEV tyres, including the two reference CPX tyres of ISO/TS 11819-3. The other tyre models were not explicitly given, but according to pictures and designation in the article, EV tyre models are likely to be the Continental eContact BLUECO 195/50R18 and the Michelin Energy E-V 195/55R16. The drum was covered with a replica of a road surface and three different surfaces have been tested for all tyres: a rough surface dressing 8/10 (SD 8/10), an experimental Poroelastic Road Surface (PERS) and a Dense Asphalt Concrete 0/12 (DAC 0/12) which is a rather typical road surface. Considering noise level at 80 km/h, it was observed that EV tyres are not quieter than ICEV tyres. In fact, on DAC 0/12 and PERS noise emitted by EV tyres is on average level, while EV tyres are the noisiest on SD 8/10. However, there is some ambiguity to these results as the influence of tyre size on the noise emission is not properly considered. In [75], the study was extended to four EV tyre models compared with nine ICEV tyre models, rolling on five different types of road surfaces. Additionnally to the PERS and the SD 8/10 used in [74], replicas of a DAC (with no specified NMAS), of a DAC 0/16 and of an ISO reference surface have been used during the measurements. The tested EV tyre models are given in Figure 4-24.

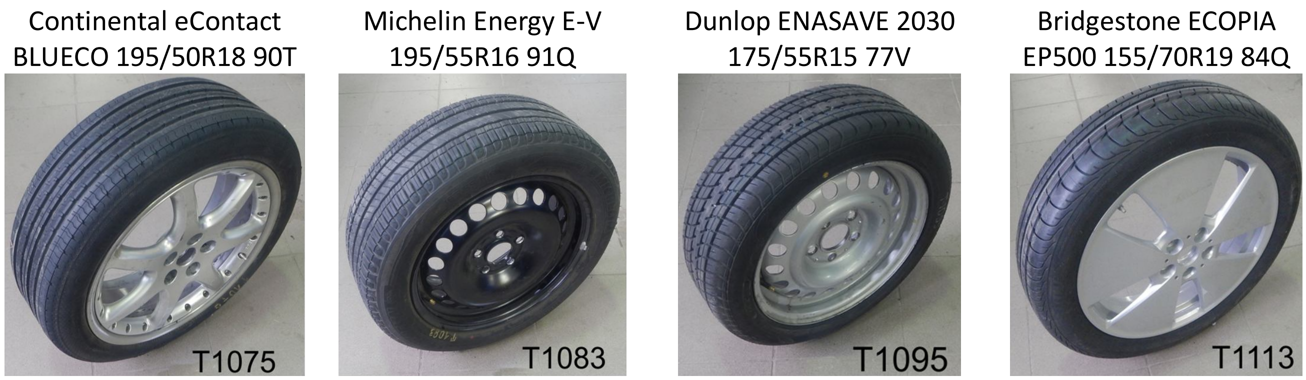


Figure 4-24 EV tyre tested on the laboratory drum facility of TUG in [75].

Based on the fact that the noise ranking of tyres was very similar for all tested speeds between 30 km/h and 100 km/h, the analysis was performed at 80 km/h. The conclusion was that average Sound Pressure Levels (SPL) of EV tyres are similar to the average SPL of ICEV on the different road surfaces but PERS, for which EV tyres are less noisy than ICEV tyres. These results are illustrated in Figure 4-25 for the DAC and the PERS at 80 km/h.

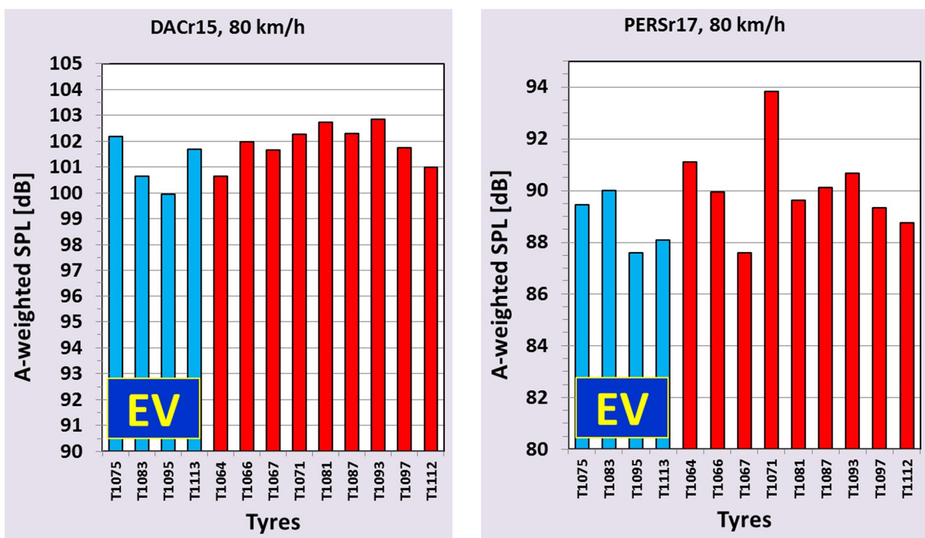


Figure 4-25 Noise levels of EV and ICEV tyres tested on the laboratory drum facility of TUG in [75]. ICEV tyre dimensions are 195/50R15 for T1071, 195/60R15 for T1066, T1067 and T1112, 195/65R15 for T1081 and T1093, 195R14C for T1087 and 225/60R16 for T1064 and T1097.

The rolling resistance of the EV and ICEV tyres was also measured according to ISO 28580 on the SD 8/10 and the DAC 0/16. The coefficient of rolling resistance on these rough surfaces was 15 to 20% lower for EV tyres in comparison with ICEV tyres.

Results concerning CPX measurements on several road surfaces in Norway and in Poland have been reported in [76] and [77]. The same EV tyre models as in Figure 4-24 have been tested and compared to different ICEV tyre models representative of the market. The CPX noise levels are analysed at 50 km/h, which was a common vehicle speed on the different test sites. A total number of 14 surfaces have been tested (7 in Norway and 7 in Poland), including several dense Stone Mastic Asphalts (3 SMA 8, 7 SMA 11 and 2 SMA 16), a Double Layer Porous Asphalt 8/16 (DPAC 8/16) and an experimental PERS. Figure 4-26 shows the CPX noise levels obtained by SINTEF on a new smooth SMA 11, a rough SMA 16, the DPAC 8/16 and the PERS, taken from [77]. On the four tested road surfaces, EV tyres were the quietest or among the quietest tyres. Such ranking was not found on the drum facilities of TUG. Compared to the reference surface SMA 16, the noise reduction was found to be about 2 dB(A) on SMA 11, 7 dB(A) on DPAC 8/16 and 11 dB(A) on PERS. With a low noise SMA 8 surface, the noise reduction is 5 dB(A).

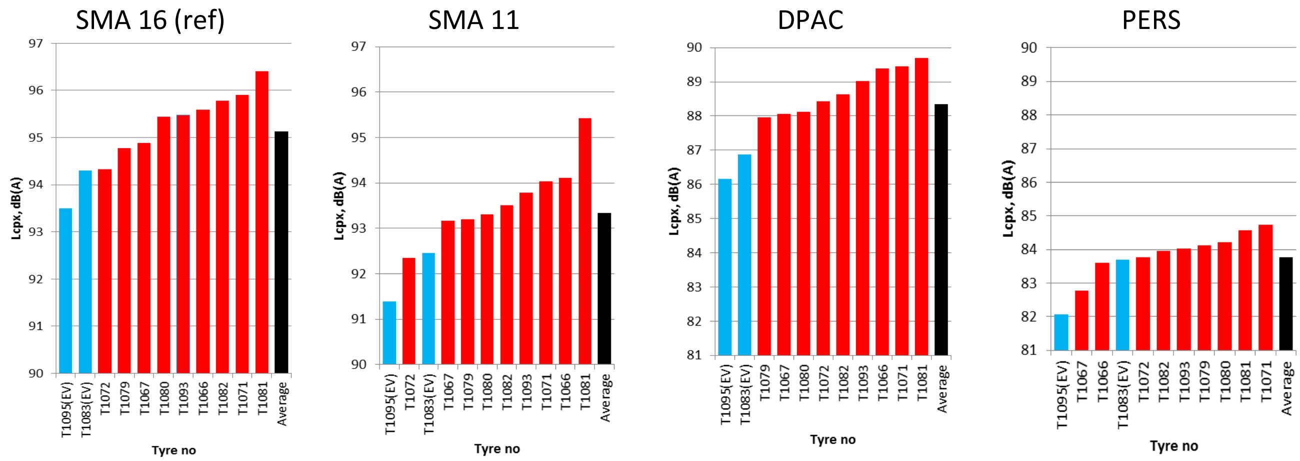


Figure 4-26 CPX noise levels measured for different EV (blue) and ICEV (red) tyre models in [77].

Finally different scenarios have been tested in [77] in order to assess the potential reduction of overall road traffic, when a combination of quiet EV tyres and a low noise road surface are used. The study is based on a noise calculation method (TRENACAM) for four different road categories with different traffic conditions: a motorway, a rural trunk road, an urban city trunk and an urban access residential. Then, on each road category 6 different scenarios have been tested: a reference road surface (DAC 0/11) with average tyres (scenario 1), the same reference surface but replacement with best EV tyres (scenario 2), replacement with SMA8 and best EV tyres (scenario 3), replacement with DPAC and average of EV tyres (scenario 4), replacement with DPAC and best of EV tyres (scenario 5), and replacement with PERS and best of EV tyres (scenario 6). According to the conclusions, scenario 1, which corresponds to a “do nothing” scenario and only relies on the effect of EU Directive 540/2014, will only give a small reduction of L_{den} noise levels of about 1.5 dB(A) in 2030. By a combination of low noise (EV) tyres and low noise road surfaces, a reduction of L_{den} noise levels of 4 to 7 dB(A) can be estimated, depending on the choice of the road surface. As can be seen in Figure 4-27, in the case of an urban access residential road category limited at 30 km/h, the best combination for noise reduction are DPAC or PERS road surfaces combined with the best EV tyres. It is also noticed that an increase in the share of EVs in the total mix of traffic up to 25 % only have a minor effect on the L_{den} noise levels (less than 0.5 dB(A)).

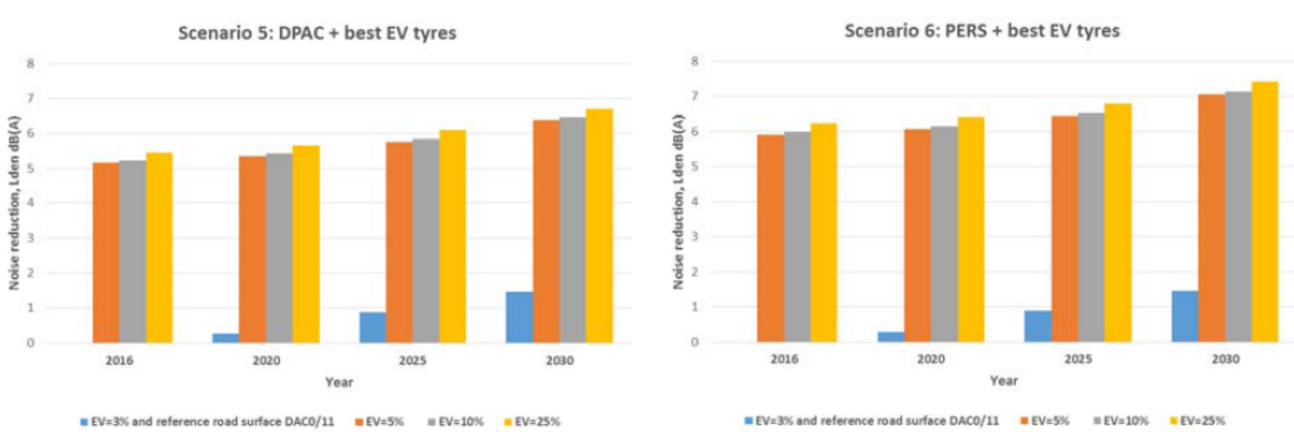


Figure 4-27 Reduction of L_{den} noise levels obtained between 2016 and 2030 with the best scenarios 5 and 6 for the urban access residential road category limited at 30 km/h [77].

FOREVER project (2013-2014): During the European FOREVER project, the influence of potential and dedicated tyres for electric vehicles was studied within Work Package 3 [78], which primary goal was to study the impact of "low-noise" tyres, according to EU exterior noise label, on electric vehicle noise emission. Paper [79] also gives a summary of the main content of WP3 of the FOREVER project.

Based on a market study of tyre models available for EVs by the end of 2013, nine different tyre models have been selected to investigate the tyre influence on rolling noise from electric cars. The selection was mainly based on the criteria of low rolling resistance label, since low energy dissipation is a main condition for extending EV range. The selected tyres are given in Figure 4-28: tyres A to H had the same dimensions 205/55 R16 and were mounted on a Renault Fluence Z.E., while tyres I had dimensions 195/55 R16 and were mounted on a Renault ZOE. Controlled Pass-By (CPB) measurements have been performed according to ISO 11819-1 standard, i.e. with a microphone on the road side at 7.5 m from the driving lane and a height of 1.2 m. The test vehicle was driving at a constant speed between 30 km/h and 130 km/h. The road surface of the test section was a Dense Asphalt Concrete (DAC) 0/11.

Abbreviation	Brand	Model	Dimensions	EU Label
A	Dunlop	Sport BluResponse	205/55 R16 91H	B/A/68
B	Goodyear	Efficient Grip	205/55 R16 91H	C/C/68
C	Kumho	Ecowing ES 01 KH27	205/55 R16 91V	B/B/67
D	Pirelli	Cinturato P1 Verde	205/55 R16 91H	B/B/70
E	Toyo	NANOENERGY 2	205/55 R16 91V	A/C/70
F	Bridgestone	Ecopia EP150	205/55 R16 91H	B/B/69
G	Michelin	ENERGY SAVER	205/55 R16 91W	B/A/70
H	Hankook	Kinergy Eco K425	205/55 R16 91H	B/B/70
I	Michelin	ENERGY E-V	195/55 R16 91Q	A/A/70

Figure 4-28 Set of tyre selected for tyre/road noise measurements in WP3 of FOREVER project [79]. The EU label is in the format Rolling Resistance/Wet Grip/Noise Emission.

Figure 4-29 gives the maximum pass-by noise levels measured for the different investigated tyre models. The difference between two investigated tyres never exceeded 3.6 dB(A) for lower speeds (20 – 50 km/h), and for speeds between 50 and 120 km/h the spread never exceeded 2.4 dB(A). It was concluded that rolling noise from EVs did not differ significantly from ICEVs, and that no amendment was necessary for rolling noise of EVs in the CNOSSOS-EU model. This will be further detailed in section 1.6.

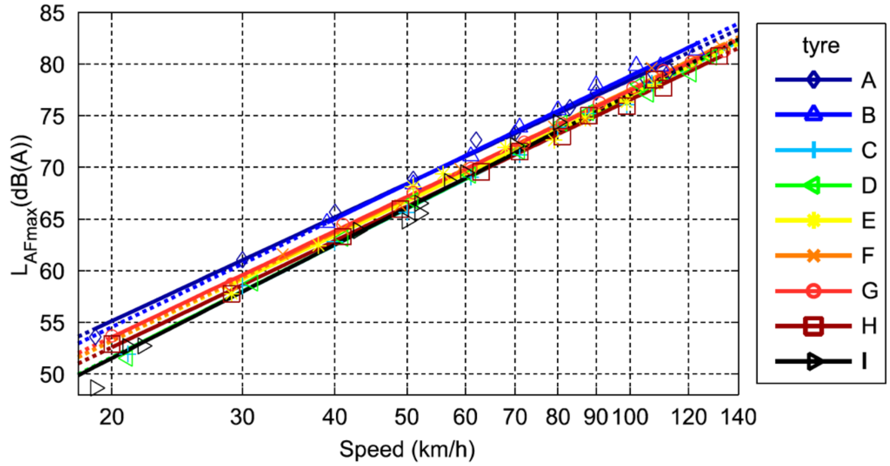


Figure 4-29 Maximum pass-by noise levels measured for the tyres investigated in [79].

4.1.3 Acoustic Vehicle Alerting System (AVAS)

For the safety of pedestrians and other road users, European and international texts specify provisions for an alerting sound system installed on light electrically driven vehicles. As they may be too quiet for auditory detection, this equipment will soon be operational on all new electric vehicles at low speed but is already effective on some EVs.

4.1.3.1 Regulatory elements

The European regulation 2017/1576 [80], amending regulation (EU) 540/2014 [81], requires hybrid electric and pure electric vehicles to be equipped with an alerting system emitting an artificial sound in some operating conditions[5]. It came partially into effect from 1st July 2019 and will be fully on 1st July 2021 onwards, according to the date of vehicle type approval. The system shall automatically generate a sound at least from start up to 20 km/h and during reversing. It may also make sound when the vehicle is stationary. The driver may temporary switch off the system, which will automatically resume when restarting the vehicle.

The AVAS sound shall be continuous, similar to the one from an equivalent conventional vehicle, informing the road user on the vehicle behaviour by a frequency shift indicating acceleration or deceleration in synchronisation with speed.

The regulation specifies an overall minimum sound level. This corresponds to an A-weighted peak sound pressure level of 50 dB(A) at 10 km/h and 56 dB(A) at 20 km/h in the forward direction (47 dB(A) in the reverse direction), measured at a distance of 2 m (height 1.2 m) from the lane centre[6]. Nevertheless, the alert sound should not exceed the approximate sound level of a conventional passenger car in the same conditions. In any case, there is a maximum overall sound level specification of 75 dB(A) at a distance of 2 m (corresponding to 66 dB(A) measured at 7.5 m). If the vehicle by itself radiates a noise larger than the minimum requirements with a margin of +3 dB(A), no AVAS equipment is needed.

[5] The European regulation is based on Regulation No 138 of the Economic Commission for Europe of the United Nations (UNECE) [82]

[6] Sound levels correspond to measurements performed on a road surface in accordance with ISO 10844:2014.

In addition, the sound signal shall have at least two one-third octave bands in the range 160-5000 Hz, one of them below or equal to 1600 Hz, with minimum sound pressure level requirements in each band. At least one tone shall shift proportionally with speed when driving in the forward direction.

4.1.3.2 Exterior noise contribution of AVAS

Many research projects and studies have focused on alerting signal, considering sound design and signal characteristics for improving the detectability of electrically driven vehicles. Most of them were conducted before the publication of the ONU and European regulations. Now that the framework is officially set and that vehicle manufacturers are equipping their electric vehicle models with sound alerting systems accordingly, the concern beyond safety is its actual environmental impact. Although not targeted in the scope of LIFE E-VIA actions, it is a possible component of EV noise emission at very low speeds, both inside and outside the vehicle. It actually refers to a low-level noise source, but occurring – purposely – in an operating range where other sources are quiet. However, it intends to offer both a low environmental noise impact and a high detectability, favouring comfort at the expense of nuisance [83]. On a Japanese experimental study considering the noise emission of a set of marketed hybrid and electric (including a fuel cell) vehicles, pass-by measurements were performed on different sites [84]. Results given on the global noise levels did not inform whether AVAS sounds were available or contributed to the overall noise. However, noise spectra with and without the AVAS signal on one hybrid vehicle and the fuel cell vehicle did not point out any significant difference (Figure 4-30). The measurement speed for this spectrum comparison was not indicated.

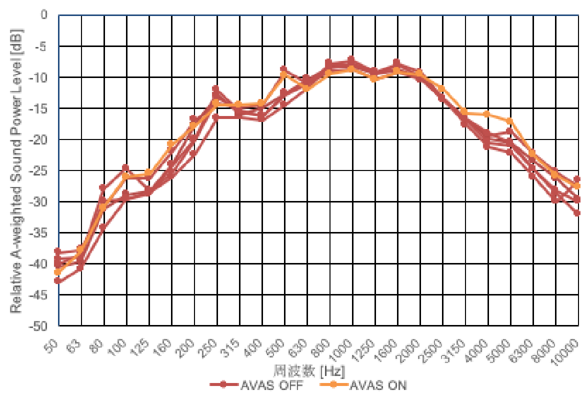


Figure 4-30 Relative sound power level of a fuel cell vehicle with and without AVAS signal (from [84])

A previous study involving on-board acoustic measurement in the motor nearfield of several EVs showed the contribution of the AVAS signal on the spectrogram of a Renault Zoe during run-up and run-down [49]. This was also present in the Prominence Ratio result (Figure 4-31). However, the AVAS signal was not clearly visible on the same test with a Smart Electric. Nevertheless, the on-board recording does not necessarily predict the exterior sound rendering after transfer through the car body.

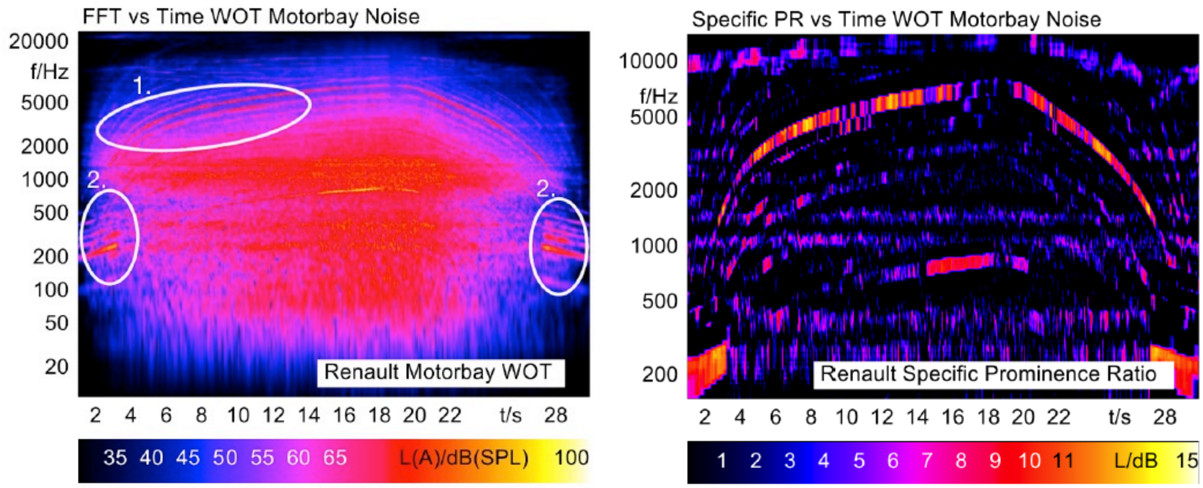


Figure 4-31 Spectrogram (left – (2.) highlights the alert sound contribution) and corresponding Prominence Ratio (right) of the nearfield sound of a Renault Zoe during run-up and run-down (from [49]).

A specific study, recently carried out on a set of seven marketed electric vehicles, provided precise numerical results on exterior noise emission [85]. Six of the EVs were equipped with an AVAS, which could be manually switched off for five of them. The peak level (L_{AFmax}) at constant speed pass-by was measured on microphones located at 7.5 m from the lane centre on both sides of the vehicles, on an asphalt concrete road surface 0/11. The speeds tested were 10, 20 and 30 km/h in a low background noise surrounding, ensuring a difference with vehicle peak signal larger than 10 dB(A) in most cases, occasionally lower at 10 km/h but always more than 7 dB(A). By comparing noise levels at pass-by with and without AVAS, the highest noise increases occurred at 10 km/h, ranging from 1 dB(A) – concerning the otherwise noisiest vehicle – to 11 dB(A) for one of the otherwise quietest vehicles. At 20 km/h the increase ranged from 0 to 5 dB(A), whereas there was no noticeable difference at 30 km/h. The significant noise level increase at very low speed by some EVs, when the AVAS was on, may have an impact on the environmental urban noise and the authors raised the question of the balance between soundscape quality and road safety.

4.2 Connection and implication for LIFE E-VIA actions

In this section, a literature survey on noise source emission of EVs has been performed. Existing studies have found that for an electric vehicle, tyre/road noise is dominating propulsion noise for a speed of 30 km/h and above. Thus, in the perspective of growing electric mobility in urban area, the choice of low noise tyres and quiet road surface is essential for noise reduction. It was projected that the combination of the best EV tyres and the most acoustically efficient road surfaces could lead to significant noise reduction, while an increase in the share of EVs in the total mix of traffic would only have a minor effect. Therefore, one of the main objectives of the LIFE E-VIA project is to reduce noise in urban areas through the implementation of an optimised solution of road surface and tyres for EVs. This will be performed at different technical levels in most of the implementation actions B of the project.

However, the literature review points out a lack of information on tyres, pavement types and test sites involved in experimental studies, leading to some uncertainties in the analysis. For instance, the road surface properties (texture, absorption, mechanical impedance) are rarely reported in details, the choice of tyres regarding use on EVs is not always justified and the background noise on the test sites is not systematically quantified while being a key difficulty when studying EVs at low speed, even more for quiet tyres rolling on a low noise road surface. Therefore, in action B2 of LIFE E-VIA, measurement campaigns will be performed on the reference test track of

Université Gustave Eiffel in Nantes (France) which benefits of a relatively low background noise (about 40 dB(A)). Six existing road surfaces with fully characterised properties will be considered for noise measurements (pass-by and close-proximity) of different EV models in action B2.1. In action B2.3, a prototype of low noise road surface developed during the project will be built and fully characterised on the same site. The subsequent tyre tread pattern optimisation within action B2.4, by successive declinations of a top market tyre from Continental (cf. report on preparatory action A3), will definitely constitute an original approach within the project.

Moreover, a main difficulty in existing studies is the separation of noise sources at low speeds, i.e. propulsion noise and tyre/road noise. At the present stage, no precise quantitative knowledge of the exterior noise emission from the electric motor/propulsion in real driving conditions was found in the literature. Although the potential for reduction relatively to conventional vehicles is proved, the exact contribution of driveline differences is hard to estimate from vehicle comparisons since in existing studies other parameters (vehicle or tyre models, road surfaces…) often change simultaneously. Action B2 of LIFE E-VIA will try to overcome these difficulties based on different strategies. First, pass-by noise levels of a Renault Kangoo ZE model will be compared to those of an equivalent Kangoo ICEV fitted with the same set of test tyres, in order to avoid a bias in rolling noise emission. These test tyres will also be characterised by Continental in laboratory within action B7, dealing with the holistic performance of tyres. Second, the noise of the different EV models involved in action B2 will be systematically measured with a microphone antenna when rolling on a smooth road surface conforming ISO 10844. This kind of smooth road surface should minimize the rolling noise contribution and will permit a correct spatial separation of noise source between front (rolling noise only) and rear wheels (propulsion noise and rolling noise), for each tested electric vehicle. The microphone antenna is also less sensitive to background noise due to its directivity. This methodology will give the contribution of both kind of sources in terms of overall and frequency noise levels, leading to important information regarding rolling noise and optimisation of tyre/road interaction, for optimal mix and tyre developments in actions B1 and B2.4/B7 respectively.

The data acquired within action B2 will feed other main actions of the LIFE E-VIA project (B1 and B3 to B6) with solid knowledge regarding noise emission properties of EVs and the specific optimisation of tyre/road noise reduction in the context of an electric vehicle fleet in urban area.

5 Changes in noise perception

5.1 State of knowledge

According to [86], in Europe 22 million people present chronic high annoyance, whereas 6.5 million people have chronic high sleep disturbance: these effects are significantly related to environmental conditions.

Annoyance is defined as “a stress reaction that encompasses a wide range of negative feelings, including disturbance, dissatisfaction, distress, displeasure, irritation and nuisance. The individual response to noise depends not only on exposure levels but also on contextual, situational and personal factors. It can initiate physiological stress reactions that, if long-term, could trigger the development of cardiovascular disease.” [86].

Specifically, road, rail, aircraft and industrial noise are among the main environmental risks which affect health. It is estimated that environmental noise provokes health effects including annoyance, sleep disturbance and ischaemic heart disease. The World Health Organization demonstrates negative effects on health at levels below the thresholds reported by the Environmental Noise Directive 2002/49/EC (END). In Europe, road traffic noise, which is the most dominant source, is the main environmental problem. Approximately 20 % of the EU population is subjected to harmful traffic noise levels. As a matter of fact, it is estimated that 113 million people live in noisy areas and therefore they are affected by long-term day-evening-night traffic noise levels higher than 55 dB(A). 113 million is a significant number, compared to people exposed to railway noise (22 million), aircraft noise (4 million) and noise produced by industries (less than 1 million). However, these values are assumed to be underestimated. Furthermore, the END does not cover all the typologies of areas across Europe.

As above-mentioned, noise from road traffic exceeds the one generated by rail, aircraft and industry sources. This aspect is related to the fact that the extension of the road network is greater than that of other noise sources, at least at the European level. Moreover, in the European Union, it is estimated that there are approximately 500 cars per 1000 inhabitants, which entails a widespread use of road vehicles [87]. It is estimated 15 % of the population are exposed to high levels of road traffic noise during the night-time period. Also, in this case, these END values are expected to be higher. Nevertheless, a wide range of variation can be noted in the number of people exposed to road traffic noise inside urban areas among countries. For example, the percentage of inhabitants exposed to road noise levels of 55 dB(A) L_{den} in urban areas is more than 50% or even higher during the day-evening-night period.

Regulation (EU) No 540/2014 on the sound level of motor vehicles and of replacement silencing systems is the relevant regulation concerning road traffic noise, which requires subsequent amendments regarding the acoustic vehicle alerting system for electric and hybrid vehicles as well.

In urban areas, more than 50 % of the actions, taken for overcoming the issue, aim at reducing and managing noise by intervening on the noise source. The mitigation of noise at the source is also mainly used in areas outside cities which present a significant number of railways (52 %), airports (70 %) and roads (39 %) [86]. Land use and urban planning are interventions which can be considered to manage and reduce noise, alongside other environmental requirements, such as air pollution’s control, which often offers co-benefits. Nevertheless, not all actions weigh the same on the causes of stress. Additionally, the estimations of cost-benefit for these kinds of interventions have a more favourable effect if the results positive impact on both air quality and noise.

In this perspective, on the one hand in urban areas, where speeds are low and traffic is commonly stationary, the presence of electric vehicles has a positive effect on environmental noise; on the other hand, the incidence of electric vehicles should be insignificant in major roads and motorways, characterised by higher speeds [88].

Positive acoustic effects for electric vehicles are noted at low speeds (10-25 km/h), thanks to the predominance of the propulsion noise. As a matter of fact, in this case, electric motors are much quieter than common engine combustion vehicles. Increasing the speeds (higher than 25-30 km/h), noise, generated by the interaction between the tyres and the road, shows a more significant contribution [89], therefore the noise produced by tyre/road interaction does not differ in the same way for electric and conventionally fuelled cars at all speeds. In particular, it is noted that at 50 km/h, the noise reduction comparison between electric cars and conventionally fuelled cars has a just noticeable difference of about 1 dB [89], [90]. In any case, the above-mentioned effects at low speed can be considered for scooters, which are commonly used in the cities in the southern European countries. Scooters could be replaced with electric scooters and this action could positively contribute to the noise levels' reduction [91]. Moreover, the first findings concerning electric vehicles have been transposed into the EU Regulation No 540/2014 [81], which requires the introduction of an artificial signal for electric and hybrid vehicles. This latter aspect has been thought for helping blind and visually impaired pedestrians, in order to compensate for the difficulties in the identification of electric vehicles, for speeds up to 20 km/h. It has been demonstrated that the acoustic vehicle alerting system may negatively influence the noise benefits of electric cars at speeds lower than 30 km/h [85]. Employing both models and observational measurements, it has been noted the impact which may have the widespread of electric vehicles in urban areas. According to Campello-Vicente et al. [90], at low speeds noise levels next to a traffic lane are 2 dB higher for only conventionally fuelled cars, compared to the one with only electric vehicles. Another positive result comes from the COMPETT Project, which underlines how the conversion of existing vehicle traffic in electric-vehicles-only would provide a reduction of 0.6 dB at 30 km/h and 2.5 dB at 20 km/h [56]. As evidenced by other publications, the widespread of electric cars replacing conventionally fuelled cars would have a significant contribution on roads in particular in conjunction with low mean traffic speed [92]. Carried-out studies have been widely accepted. Germany is an example of this: with the proposal to replace 1 million fuel-powered vehicles with electric vehicles by 2020, it estimates a noise reduction of 0.1 dB in urban roads [88].

Electric Vehicles (EVs) are characterised by reduced noise emissions compared to Internal Engine Combustion Vehicles (ICEVs). Particularly, sound originating from ICEVs contributes to masking unwanted sound sources and it also provides audible feedback of operation. Traffic noise mainly consists of powertrain noise and tyre/road noise, the latter dominates after 40 km/h for ICEVs, whereas the threshold is lower for EVs.

The increase in various types of electric vehicles creates new challenges concerning noise control and sound quality. They are generally quieter and characterised by multiple high-frequency tonal components, which may be perceived as annoying, sharp and aggressive in many different contexts. Thus, they may lower the impression of overall sound quality satisfaction. In order to fulfil the customer's expectations of interior acoustic comfort, further knowledge needs to be gained about the perception of tonal components appearing in a mix of random noise from wind and tyres.

In recent studies, some authors have demonstrated that when driven in electric mode, low-noise vehicles may be so quiet that they can be dangerous for pedestrians and bicyclists [93]. Others pointed out that vehicle accident statistics are still insufficient or incomplete and cannot provide a reliable outcome [89], [94], [95], [96]. Nevertheless, several studies proved that quiet approaching vehicles are harder to hear than traditional ICE (internal combustion engine) vehicles, leading to a suspected higher risk for other road users [97], [98]. That is why some nations or country unions have been preparing guidelines/requirements/regulations for Acoustic Vehicle Alerting Systems (AVAS) to be installed on hybrid electric and electric vehicles [52] until the entry into force of the Regulation of the EU Parliament of 7 March 2019 establishing that since 1st July 2019 all new types of electric and hybrid vehicles in the European Union (EU) must be equipped with an AVAS.

According to Misdariis and Pardo [83], reduced noise emissions constitute one of the attractions of EVs, although it entails difficulty in detection, and it endangers pedestrians' safety. For an internal combustion vehicle, the engine contributes significantly to the overall noise made by the vehicle. Particularly at low speed, the difference between EVs and ICEVs can be over 10 dB, whereas the noise made by the tyres on the road surface becomes dominant above 20 to 30 km/h. At the speed of 10 km/h, an electric vehicle may not be detected until it is less than 5 meters away, whereas, under the same conditions, a vehicle with an engine can be heard up to 50 meters away. Blind and visually impaired subjects are the most affected by changes in noise perception, for this reason, some associations are encouraging countries to legislate on the subject. The dangerousness of silent vehicles can be established based on accident data. The latter shows a higher rate of collisions between electric or hybrid vehicles and pedestrian compared to internal combustion vehicles. Despite the expected result, it has to be considered the small size of the analysed sample due to the low percentage of this new type of vehicle in the overall fleet and the lack of accident reports for most of the low-speed-accidents. It is, therefore, necessary to reduce the overall noise level of the vehicle whilst at the same time ensuring sufficient safety for pedestrians.

In order to overcome acoustic issues, some studies are focusing on making silent vehicles audible. This solution has to be integrated into our sound ecosystems efficiently and discernibly, whilst remaining highly ecological. An approach using restricted, mastered audible signal design, is a pertinent, effective solution from the point of view of safety, ergonomics, acceptability and sound, ecology. The challenge provides the highest detectability while ensuring the lowest noise impact on the environment. Possible solutions may provide non-acoustic or acoustic measures addressed to drivers or pedestrians. They have to be informative for the driver and not disturbing for his driving activity, whereas at the same time they have to meet basic warning requirements. The idea of designed sounds has to be subjected to two main criteria: "detectability" and "unpleasantness".

In [99] prominence ratio (PR) is found to be an appropriate metric for quantifying the relative levels of the tones. The study is based on the relationship between the psychoacoustic metric (PR) and the threshold of detecting the tones and also the perceived annoyance for both constant speed and acceleration in a pure electric vehicle. The aim is to investigate at what PR level the e-motor tones could be detected and also how perceived annoyance relates to PR for different frequencies. PR is defined between 89.1 Hz and 11220 Hz.

The driving conditions consider two constant speeds (50 km/h and 80 km/h) and a 0 to 100 km/h max acceleration on a flat smooth asphalt. The listening test is conducted considering the co-driver's position as the receiver's one. From the original recordings, sound stimuli with varying magnitude of the e-motor tones are constructed.

The relationship between perceived annoyance and frequency content is dependent on the PR-level of the tones, for this reason, sounds have been grouped into three categories with different PR-level intervals: PR≤2 dB (low audibility), 3 dB≤PR≤4 dB (mid audibility) and, PR≥5 dB (high audibility).

The constant speed's listening test results reveal that below 800 Hz, a higher PR value is required for audibility compared to tones above 2.5 kHz. For all driving conditions, the perceived annoyance was relatively low with small differences between the frequency ranges for the low audibility stimuli (PR≤2 dB).

With PR≥3 dB, the perceived annoyance was significantly increased for frequencies above 5 kHz compared to frequencies below 800 Hz for the constant speed cases. The acceleration cases yielded similar conclusions. Thus, a general recommendation would be to provide a PR-level below 3 dB for tones exceeding 800 Hz. For tones with lower frequency content, the PR-level can reach values around 5 dB and still not induce high annoyance ratings. As above-mentioned, if e-motor audible feedback from driving is desired, the preferred tones would be the ones with lower frequency content.

Conducting listening tests turns out to be necessary, in order to detect people's feedback. In this perspective, [100] presents results gained in test drives, where subjects drive electric vehicles and comment on different sound concepts. Sound quality depends on cognitively processed features referenced to an assigned set of expectations. Electric vehicle technology is a new ground for automotive development and acoustical design. Using a sound synthesis tool, three sound concepts were developed: a sound resembling a combustion engine (sound 1), a modern and rather unconventional sound (sound 2), and an inconspicuous, modest sound (sound 3). In order to compare the reactions, an additional sound was considered as the original sound of the electric vehicle (sound 4). The different sound concepts were implemented and assessed by test subjects in a compact class series-production electric vehicle (Opel Ampera). The test procedure considers subjects driving 20 to 25 minutes the electric vehicle on a defined test route in the area around Aachen, Germany. The test route was chosen to provoke as much as possible relevant driving situations. To avoid any memory effects, a waiting period of several working days was set between test drives. Thus, test subjects could not recall all acoustic details and were gradually reset. During the test drives, the subjects were requested to express their feelings and associations with respect to the vehicle, its general comfort and its acoustics in their every-day life language. After the test drive, a semi-structured interview took place in the car and the subjects could explain their thoughts and feelings in detail. The experimenter asked some questions regarding their in-situ judgments and comments and they evaluated the perceived overall quality and sound quality. Afterwards, all relevant statements were identified and categorized. Moreover, the comments were classified as positive, negative or neutral, according to their connotation, and distributed in diagrams, referring to the different sound concepts over speed and acceleration. The outcomes show all sound concepts provoke positive as well as negative comments, thus they cannot lead to utmost customer satisfaction. In general, the playback synthetic driving noises led to more comments compared to the test drives without any sound playback. Obviously, synthetic sounds can additionally stimulate emotions and feelings. Cluster of comments was found in the mid-speed range with moderate acceleration and in the low-speed range with positive and negative acceleration.

In conclusion, offering synthetic driving noises in the interior of an electric vehicle has led to more comments, although it did not necessarily foster positive evaluations or perceptions of the car and its acoustics. In general, the study has shown that target conflicts occur and must be managed. For example, subjects expressed their preference for a quiet electric vehicle, but on the other hand demand adequate acoustic load feedback. Moreover, the subjects were inclined to modest sounds, which in turn lead to an increase in vehicle's transparency. A sound concept presenting a synthetic sound achieved a slightly better assessment than the original sound only condition, although even few subjects were not aware of the presence of a synthetic sound at all. It illustrates that the modest sound character is accepted leading to positive comments. But this sound does still not fully mask disturbing noises within the original vehicle sound and still evoked some negative comments as well.

In any case, it is evident that the expectations of the customers are not fixed and grounded, thus the frame of reference permanently changes and is based on previous experiences mainly related to vehicles equipped with combustion engines. As a future outlook, different approaches of synthetic driving sounds must be subject to investigation to determine their benefit for increasing perceived quality and customer satisfaction.

According to the research carried out by Head Acoustics concerning vehicle exterior noises, their general hope is raised for quieter road traffic and less noise polluted cities. At least, under certain conditions a road traffic noise reduction is possible to a certain degree. At the same time, warning and alerting signals for increasing

pedestrian safety are necessary. Even because solutions of simply playing back some additional sounds will significantly ban the risk of collisions between pedestrians/bicyclists and vehicles in general. However, politicians have already taken legal actions and measures in this sense.
Regarding the interior noise of electric vehicles, the development and conceptual orientation of sound design are not settled so far and there is no established knowledge about customer preferences, demands and needs. In fact, customers are still without deep experience with electric vehicles and therefore they cannot rely on an established set of expectations to express reliably their wishes and needs.
Based on a context-sensitive, explorative method the acceptance of different sound concepts in electric vehicles have been investigated in detail by Head Acoustics [101]. In the presented case study, the degree of acceptance of certain synthetic sounds experienced in a real electric car while driving is addressed. Although offering synthetic driving noises in the interior of an electric vehicle has led to more comments, it did not necessarily foster positive evaluations or perceptions of the car and its acoustics. Subjects expressed their preference for a quiet electric vehicle, but on the other hand demand adequate acoustic load feedback.
Finally, it must be stated that the general acceptance of certain sound concepts is far from conclusive. The comments and assessments are rather inconsistent, although trends are already observable. This observation can be interpreted as evidence for a missing established frame of reference of the test subjects. According to the analysis of interview data, it was found that the frame of reference is based on previous experiences mainly related to vehicles equipped with combustion engines and (ambiguous) information from the media about the electric vehicles' technology. Thus, the assessments vary over the test drives and from person to person leading to apparently contradictory assessments.
Further research must focus on inconspicuous sound concepts, which evoke positive emotions and feelings and at the same time is capable to mask unwanted noises caused by the electric vehicle itself. For it, different approaches of synthetic driving sounds must be subject to investigation to determine their benefit for increasing perceived quality and customer satisfaction.

To sum up, exposure to noise is one of the greatest risks to people's health and well-being in Europe. Among the various sources responsible for this scenario, road traffic noise plays a major role.
Over the years, various strategies have been adopted to reduce this source of noise, mainly by trying to intervene directly at the source.
In the last period this scenario has been partially modified by the progressive introduction of EVs which, in particular at low speeds and therefore in urban areas, have proved capable of reducing noise emissions compared to ICEV and also seem to be able to make a substantial contribution to improving air quality.
Alongside these benefits, as the presence of electric vehicles increases, there are also new challenges such as the need to ensure the safety of pedestrians, cyclists and other vehicles and to guarantee the interior comfort of electric vehicles, including in terms of acoustic quality. Scientific research on these issues is still ongoing.

Moreover, in-depth studies regarding the resulting potential variations of traffic noise's citizens' perception have been conducted mainly within the projects CityHush and FOREVER, two recent European projects focusing on EVs.

CityHush (Acoustically Green Road Vehicles and City Areas) was a three-year research project co-funded by the European Commission, under the 7th Framework Program [102]. The carried-out activity should support European noise policy to eliminate harmful effects of noise exposure and decrease levels of transport noise creation, especially in urban areas, deriving solutions that would ensure compliance with the constraints of legislative limits. A major objective of the project was to provide municipalities with tools to establish noise maps and action plans (according to the Directive 2002/49/EC) and to provide them with a broad range of validated technical solutions for the specific hot-spot problems they encounter in their specific city.

In this frame, studies and experiences have also been made in order to evaluate the differences in noise levels and people perception due to different traffic noise sources e.g. ICEV, hybrid vehicles and EVs.

In fact, many measurements were performed for the comparison of gasoline with hybrid and fully electric vehicles. The measurements took place on different proving grounds (smooth or rough), considering different tyres (standard and low noise) and test tracks and also at different inlet positions (front left and rear left). On the Goodyear proving ground, the Citroën C-Zero electric vehicle was tested with two different sets of tyres (normal and low noise) on two different road surfaces (rough and smooth). The data was evaluated in many ways using the existing variety of acoustic and psychoacoustic analyses (e.g. loudness and sharpness). The measured data of two measurement campaigns has been processed using the Acoustical Fingerprint approach based on HEAD Visor microphone array data. The applicability of the approach has been proved.

Concerning the sharpness evaluation, it is almost not influenced by the vehicle speed and it is almost independent of the sound pressure level. Furthermore, the values are only depending on the road surface and not on the tyres. Since the sharpness sensation usually correlates with noise annoyance, the observation indicates that the perceptual benefit of the smooth road surface compared to the rough road surface is less than suggested by the sound pressure level decreases, due to the slightly lower noise quality (higher sharpness values).

The carried-out measurements and simulations have permitted a detailed comparison of the different psychoacoustics parameters in the several analysed conditions.

In conclusion, regarding the sharpness evaluation, it is almost independent of the vehicle speed (for constant speed), the values are higher for the accelerated condition but decrease with the absolute speed, the road surface is more important than the tyre design with the rough surface creating the lower values. The total noise energy generated on the rough surface is higher than on the smooth surface, but it is shifted towards the lower frequencies leading to a reduced sharpness. Regarding loudness, the influence of the transmitted force on the driven tyre noise emission is more prominent, while the influence of the tyre/road noise combination on the rolling tyre noise emission is smaller.

The FOREVER (Future Operational Impacts of Electric Vehicles on national European Roads) project, funded under the CEDR Transnational Road Research Programme Call 2012 on Noise, focuses on EVs. In fact, changing public attitudes regarding sustainability and energy efficiency, the use of electric vehicles (either hybrid-electric or fully electric) on European road networks is increasing. The main focus of noise-related research has been associated with the use of these vehicles in low-speed urban environments, particularly in relation to the safety risks posed to vulnerable road users. Little research has been carried out to date on the potential noise impacts of electric vehicles on roads, which fall under the jurisdiction of National Road Administrations (NRAs), namely motorways and other primary routes.

The FOREVER project aims to address the issues on NRA roads by providing data and information focusing on the identification of the noise emission levels from electric vehicles (powertrain and rolling noise components) at speeds representative of NRA roads, including the impacts of added alert sounds and the development of input data for the CNOSSOS-EU noise model, the noise emission from low-noise tyres and tyres used with electric vehicles, and an estimation of the noise impacts of electric vehicles and low-noise tyres on NRA roads, based on different fleet compositions and different take-up rates of electric vehicles.

As mentioned in [52], the main features which distinguish the noise of electric vehicle from traditional internal combustion vehicle are directionality, frequency content and sound pressure level. From the standard pass-by tests, a collection of data has been done in order to obtain a noise database of vehicles, which can be used for studies in the presence of participants. Considering blind and visually impaired subjects' experience, it seems to be necessary to investigate the subjective response of human listeners to EV noise from national routes, in order to understand the improvement which can be introduced.

The research has aimed to develop a model of various road traffic mixes on a national routeway, therefore, it would be easier conducting studies for investigating the correlation between electric vehicles as noise sources and the human subjective responses to the noise.

For this purpose, within the FOREVER project, single mono recordings have been saved and employed to generate an auralised road traffic environment and producing various road traffic mixes of ICEVs and EVs. This procedure is a novel approach to generate auralisations of road environments in a rigorous and repeatable way and it could be used for further researches in the field of traffic noise exposure. The method used for obtaining results considers a combination of experimental noise measurement on ICEV and on EV test vehicles, which have been then processed and auralised using a software-based 3D. For the research, a road profile was used, corresponding to a national route way and varying the number of EVs.

Nevertheless, the introduction of a large number of electric vehicles on national roads will not negatively influence the subjective response of participants undoubtedly. Therefore, the experience would only be improved by the reduction of ICE vehicles.

The subjective response to noise of human listeners is widely different, therefore it is crucial to investigate the perceived character of noise emission of electric vehicles. In order to assess the noise emission of electric vehicles, an already used system of perceptual dimensions [103] has been considered.

To evaluate vehicle noise emission, time-averaged dB(A) based assessment methods - including band limited measures – are commonly used. Most of the times, these measures present difficulties in discriminate vehicle type. In particular, it is noted that these methods fail in representing the change in noise character associated with electric vehicles. A substantial difficulty in acoustics is correlating objective and subjective parameters. People are mostly familiar with road traffic noise but this subjective aspect cannot be directly translated into a decibel scale. The comparison of these aspects is based on noise mapping, which is not easily readable for non-specialists. Therefore, the FOREVER project has used a tool to make people be absorbed in the acoustic environment of a national routeway. This will be easier for estimating the possible reaction of people communicating noise data to the inexpert public.

For studying human perception and acceptability of people living close to national roads, the above-mentioned sound files, generated by the novel approach, have been considered. People could be positively affected by the presence of EVs in passing traffic. For the auralisations of road traffic mixes of ICEVs and EVs, different proportions of EVs have been considered: 0%, 20%, 40%, 60%, 80% and 100%. A bandpass filtered version of the auralisations has been produced to investigate the involvement of frequency range in subjective response.

Considering that different types of ICEVs and EVs could affect results, it has been decided to use a single ICEV and a single EV for generating road auralisations. This ensures to reduce variability and to focus on participants' responses.

An arrangement of a 250 m long road traffic environment was defined with 10 vehicles with a random spacing (from 1.7 up to 2.3 seconds) between vehicles placed in each lane. The point of reception had been set at the halfway. The produced sound files are of approximately 30 seconds and they are simulated in constant traffic flow. The sound files are generated in the time frame between the point when two vehicles had passed the point of reception in the near lane and the point when there are two vehicles which have yet to pass.

The different configurations of the road traffic environment have the aim to investigate the change in response to noise, thanks to the presence of EVs. Moreover, examining the audio files and source spectra it was decided to opt for an additional set of road environments using a bandpass filter in order to distinct frequency bands and observe a change in subjective response by the participants.

After generating the auralisations, an experiment was conducted. Thirty-one participants were asked to rate the convolved signals through a series of perceptual evaluations ("pleasant – unpleasant"; "relaxing – stressful"; "clean – dirty"; "quiet – loud"; "attractive – unattractive", as reported in [103]). The participants were informed that the sounds they would hear were the sounds of traffic in a residential area on a major road. For avoiding participants to set a two-option perceptual evaluation, a slider, moving between the two opposite statements, was provided. Participants, listening to audio samples in random order, using headphones, rated each sample on the five scales.

The overall outcomes, presented in Figure 5-1, join together the five scales. The rating is divided from 1 to 10, stating that the higher the score the more positive the perception is. Results show that the highest proportions of EVs in the traffic noise obtain a higher score in human perception.

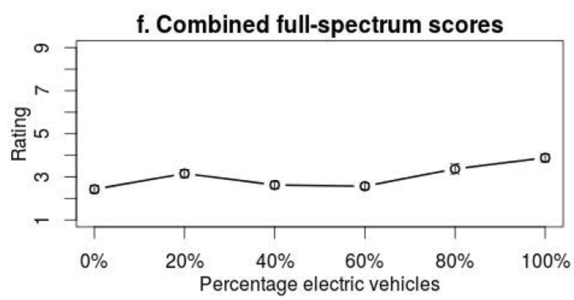


Figure 5-1 Error bars represent standard errors of the mean. Image taken from [52].

The bandpass-filtered versions of the sounds were tested by participants as well, to observe the change in subjective response related to frequency components of the traffic noise. In particular, the association with good or bad ratings was an aspect of interest. In Figure 5-2, the overall pleasantness ratings have been compared between recordings of two opposite cases of road traffic mixes of EVs and ICEVs: 100% EVs and 100% conventional vehicles. The columns, shown in the figure, are presented for unfiltered sounds and for sounds filtered in the frequency bands: <100 Hz, 100-500 Hz, 500-2000 Hz, and >2000 Hz.

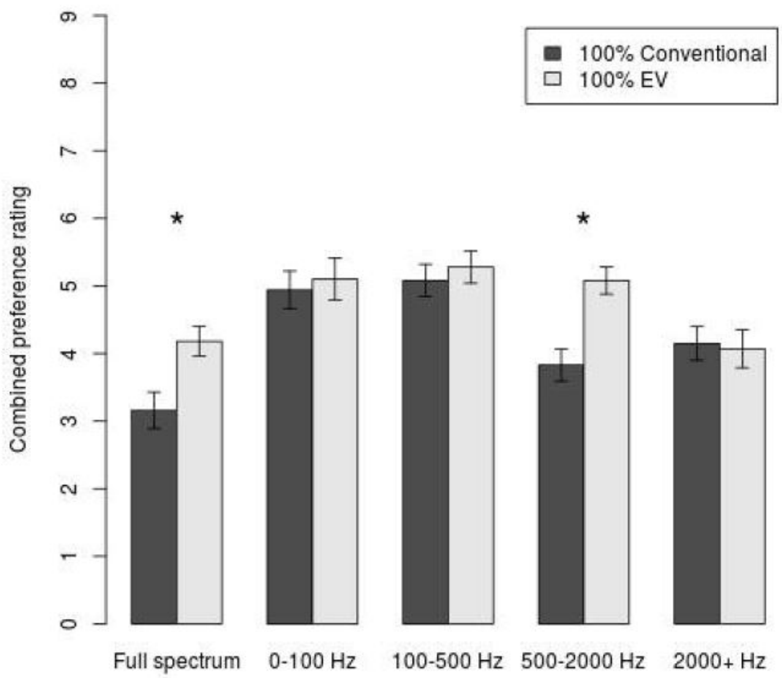


Figure 5-2 Mean ratings of traffic sounds for either 100% conventional vehicles or 100% electric vehicles (EV) as a function of available frequency information. Image taken from [52].

For all the unfiltered and filtered sounds, except for 2000 Hz, traffic noise was rated more favourably for only-EVs environment rather than for 100% conventional vehicles. This outcome suggests increasing the number of EVs on national roads, in order to improve the auditory experience of people living and working nearby. The results are related to the fact that 500-2000 Hz frequency band, contains most of the engine noise for ICEVs, hence the preference for 100% EVs. Therefore, this proves the human perception of vehicles persuades to associate the sound of the vehicle with the noise generated by the engine, which is particularly evident for conventional cars. In conclusion, the more the presence of EVs in the traffic mix the more the subjective improvement will be stated in the response of human listeners [52].

A more detailed analysis was subsequently undertaken for considering the introduction of a beneficial level correction factor for the model of EV traffic mixes. The results on the participants imply that EVs may improve subjective perception, reducing noise annoyance, whereas the effects on the overall exposure level are not proportional. This aspect can be explained as ICEVs show a lack of tonal noise contributions, which annoys although they are not significantly involved to the overall level.

Over the years, the subjective response of humans to noise exposure has been supplied with new advanced annoyance metrics. This is the case of aircraft noise, which has requested the application of more advanced noise metrics e.g. EPNL (Effective Perceived Noise Level) in order to consider additional features and to study the nature of this noisy event.

Subjective and objective measures are difficult to correlate as the human response to noise exposure is complex and related to different features. The main psychoacoustic parameters which have to be considered are loudness, sharpness, roughness/fluctuation strength, tonality.

Currently, there are numerous annoyance metrics, although none of them addresses all the features which affect annoyance. It can be stated a similarity between aircrafts and vehicles, which allows investigating the differences in ICEV and EV noise annoyance using metrics developed for aircraft noise.

There are three annoyance metrics developed for the aircraft noise issues, which have been considered suitable for the FOREVER project: PNL (Perceived Noise Level), Tone Corrected Perceived Noise Level (PNLT) and the Effective Perceived Noise Level (EPNL). Their calculations were based on the document of FAA [104].

For conducting the investigation within the FOREVER project, measurements of ICEV and EV, already used for the participants, and the ones of an additional ICEV have been employed as the initial inputs for the calculation of the annoyance metrics. The following three vehicles have been used: Citroën C-Zero (EV); Renault Twingo (ICEV), Peugeot 107 (ICEV). A sample rate of 32768 Hz has been used for the measurements for a time duration of 20 seconds using a vehicle speed of 90 km/h.

The 20-second record was split into sections of 0.5 seconds. For the calculation of PNL, every section was processed and a 1/3 octave band analysis was performed between 50 Hz and 10 kHz, using a linear filter in accordance with the standards (IEC 1260:1995 and ANSI S1.11-2004). These results have been used to generate a spectrogram of the EV and ICEV. In particular, results from Citroen C0 and Renault Twingo are shown in Figure 5-3 and Figure 5-4.

As expected, there are significant differences between the ICEV and EV pass-by data. As a matter of fact, the ICEV shows a higher overall level for each octave band. Moreover, there are additional low-frequency tones and high-frequency engine tones, displayed in the timeframe after the vehicle has passed the microphone location of about 10 seconds.

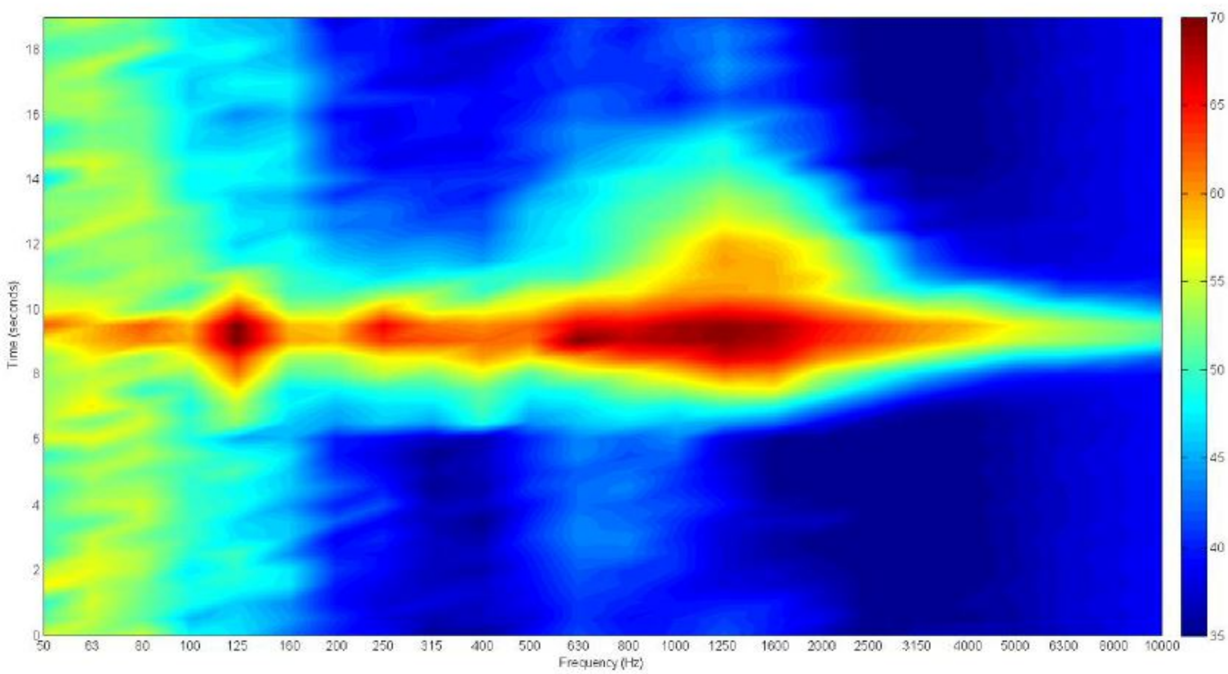


Figure 5-3 Spectrogram of an ICEV pass-by. Image taken from [92].

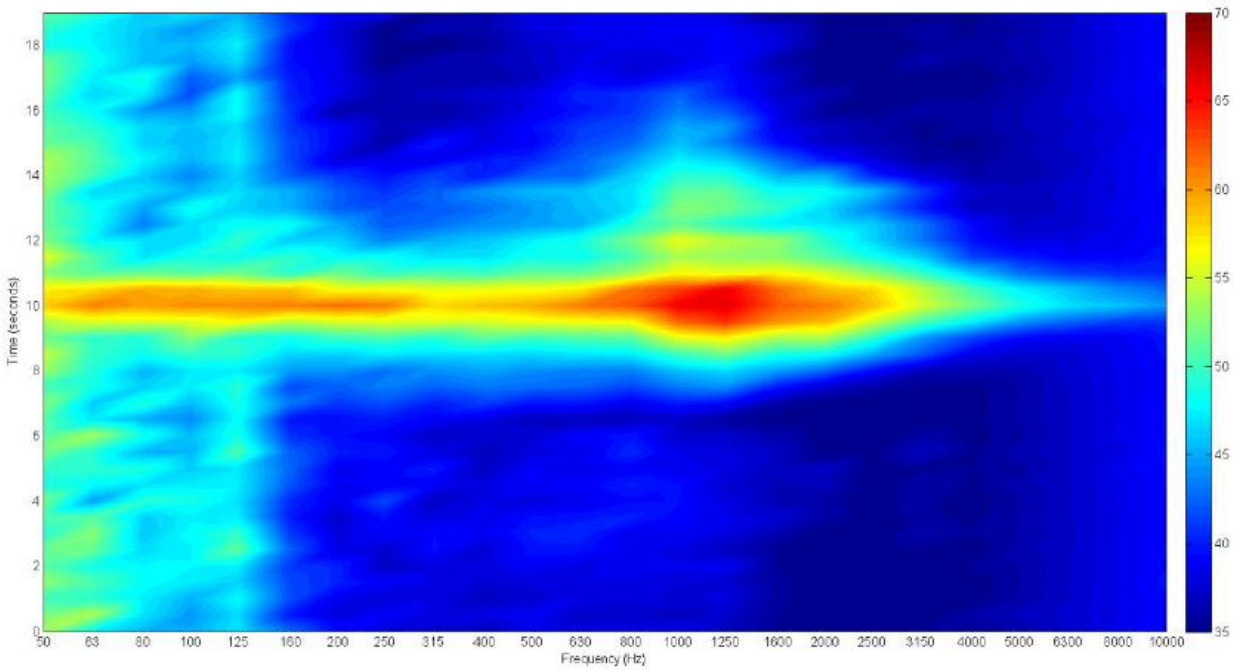


Figure 5-4 Spectrogram of an EV pass-by. Image taken from [92].

The used standard procedure considers the 1/3 octave band spectra in combination with equal noisiness curves to achieve a single Noy value. As explained in [91], "the unit Noy is common when addressing the subjective experience of noise and 1 Noy is defined as the noisiness value a person would assign a 1-octave wideband noise, centred on 1kHz with a level of 40dB. A sound that a person judges as twice as noisy is assigned a value of 2 Noy. Standard procedures have been developed for the estimation of noisiness from spectral data through the use of equal noisiness curves, as shown in Figure 5-5.". The sections of 0.5-second data are therefore used for generating the Perceived Noise Level. PNL is calculated for including the effects of level and frequency content on noise annoyance. The Noy values are summed for each 1/3 octave band and, in this way, a single PNL value for every 0.5 seconds of the pass-by is produced.

PNL could be negatively influenced by the tonality of a sound, which is an aspect that leads to an increased experience of annoyance in the listeners. For this reason, a correction factor has been used for each 1/3 octave band. The Tone Correction Factor is calculated for each band where this is the case and the largest correction factor C_{max} is used to calculate the PNLT by PNLT=PNL+C_{max}" [91].

The results of the explained procedure are shown in Figure 5-6, where the following values are highlighted: PNL (red circles) and PNLT (blue triangle).

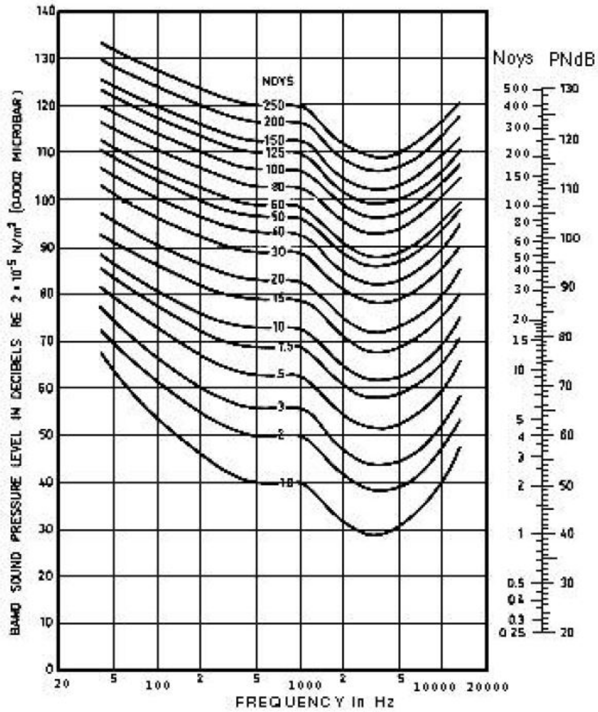
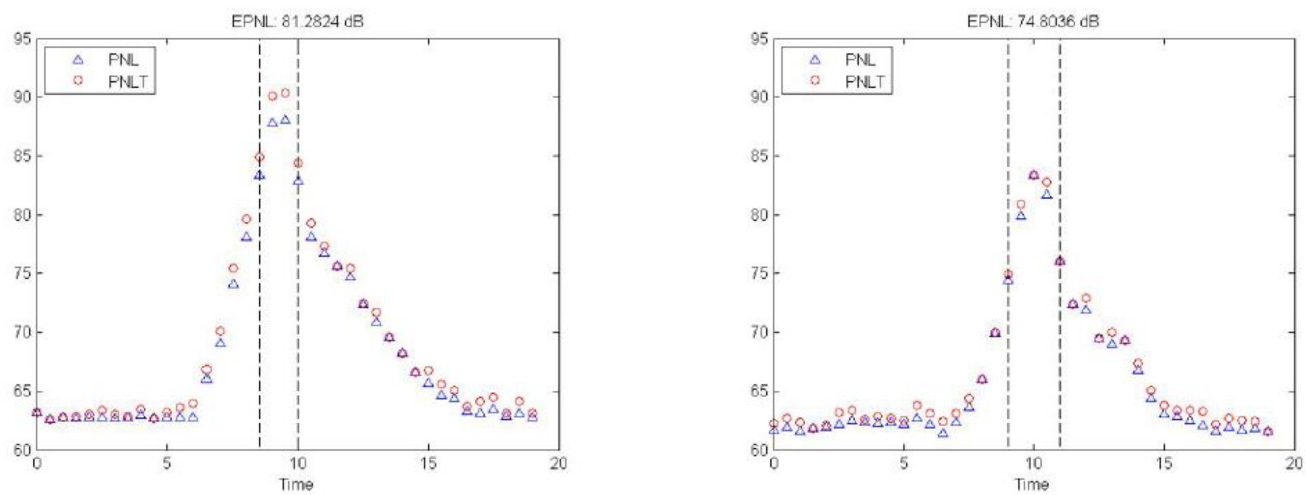


Figure 5-5 Equal Noisiness Curves and the Noy scale [92].



(a) IC PNL and PNLT, ENPL values

(b) EV PNL and PNLT, EPNL values

Figure 5-6 PNL, PNLT and EPNL values for different vehicles. Image taken from [92]*.*

Two different Tone Correction Factors have been applied for PNL and PNLT values, as a difference in tonality has been noticed between ICEV and EV. For a more precise evaluation, a different window has to be chosen: a time frame around the peak instead of the 20 seconds pass-by measurement. Moreover, the comparison between ICEV and EV makes use of the procedure for Effective Perceived Noise Level. The window correction is dependent on the points, marked with black dashed lines in Figure 5-6, representing the approach and receding phases of the pass-by. As observed from the obtained values, the Effective Perceived Noise Level (EPNL) is crucial for considering the implications of level, frequency content, tonality and duration. Hence, EPNL can be used for the comparison of noise annoyances.

Two level correction factors may be considered for comparing ICEV and EV noise annoyance. The first is the Tone Correction Factor, which has been used for the PNLT values of the ICEV and EV pass-by tests. As the EV noise has fewer tones, a lower Tone Correction Factor is defined. A reduction in terms of noisiness from an ICEV to an EV traffic mix translates into a reduction of the Tone Correction Factor for EVs. The frame considered for level correction factor is the region +/- 10 dB from the peak value. The other possible level correction factor can be calculated as the difference between the peak SPL and the EPNL value of the pass by test. It is noted that EPNL value will be much closer to the peak for EVs than for ICEVs. This aspect is again linked with the lack of tones of electric vehicles.

Table 5-1 ICEV and EV pass-by annoyance metrics. Table taken from [92].

Vehicle	**Max PNL**	**Max PNLT**	**Average C_{max}**	**EPNL**	**L_{afmax}**	**L_{fmax}**
Renault Twingo	88.08	90.33	2.15	81.28	88.66	92.27
Peugeot 107	86.75	87.8	1.09	77.77	83.45	90.94
Citroen C-Zero	83.38	83.41	0.61	74.8	84.26	86.85

As shown in Table 5-1, Max PNL, Max PNLT, Average C_{max}, EPNL and L_{afmax} and the L_{fmax} values are calculated for the three vehicles objects of study. There is a just noticeable difference in ENPL value comparing the electric vehicle (Citroen C0) with the internal combustion ones (Renault Twingo and Peugeot 107). On the other hand, more significant differences are shown between PNL and PNLT, which comparison is displayed in the Average C_{max} column.

The Peugeot 107, compared to Citroen C0, has stronger tonal components. Considering the values of the parameters for the two vehicles, in Table 5-1, this feature can be validated with a 7 dB difference between the L_{afmax} and L_{fmax} values for Peugeot 107. For the same reason, the low tonal components of Citroen C0 is proved by the difference of the same value, which is lower than 3 dB. Starting from the different values, shown in Table 5-1, Level Correction Factors have been calculated (see Table 5-2) with the result that a beneficial correction can be used for electric vehicles.

Table 5-2 Level correction factors. Table taken from [92].

Method	**Level Correction Factor**
Difference in C_{max} values	1.54 dB
Difference in EPNL and peak SPL values	2.11 dB

According to these outcomes, these methods demonstrate that a correlation between ICEVs and EVs is possible. Therefore, a difference in annoyance in ICEVs and EVs can be detected considering literature review and consulting standards from other fields; so level correction factors can be applied. As stated before, annoyance is the aspect that influences human response. Nevertheless, it is correlated with level, frequency content, tonality and duration, whose differences between EVs and ICEVs can be estimated and detected. Despite the various correlations, the Level Correction Factors show a stronger link with tonal components.

As the vehicle noise is mainly due to the engine noise, the widespread of electric vehicles and, therefore, the beneficial elimination of ICEVs' engine tones, could significantly improve the human subjective response to transport noise.

In conclusion, the increase of EV traffic mixes is demonstrated to improve subjective responses thanks to a reduction in noise levels and tonal content.

As the outcomes of the FOREVER project are satisfactory, it can be stated that level correction factors should be calculated to compare all types of electric vehicles with equivalent internal combustion and use them for traffic modelling. Accordingly, a dataset of EV pass-by tests for different electric vehicle types has been defined. An analogous study should be conducted on equivalent internal combustion vehicle pass-by tests for a wide comparison. Then, starting from both ICEVs and EVs level correction factors, a suitable comprehensive level correction factor could be calculated and implemented in European standards.

5.2 Connection and implications for LIFE E-VIA actions

The spread of quiet electric vehicles involves the definition of new solutions for the detectability, while ensuring the lowest noise impact on environment. Reduced noise emissions constitute one of the attractions of EVs. In order to make vehicles noticeable, possible solutions may provide non-acoustic or acoustic measures addressed to drivers or pedestrians. Thus, it is crucial to raise people's awareness on noise pollution and correlated health effects within the LIFE E-VIA project. As above-mentioned, some studies show that drivers are inclined to inconspicuous sounds, which in turn lead to an increase of felt acoustic transparency of the vehicle. According to the research carried out by Head Acoustics, in particular, a few subjects are not aware of the presence of the sound at all. This aspect is negatively connoted as possible acoustic solutions can be determining for blind or visually impaired pedestrians. In this perspective, LIFE E-VIA actions pay specific attention to subjects' feedback, planning interviews and soundwalks, in order to deepen acoustic related issues.

In Figure 5-7 a scheme of possible inputs from the state-of-the-art analysis to each activity foreseen during Action B5 of the Project is provided.

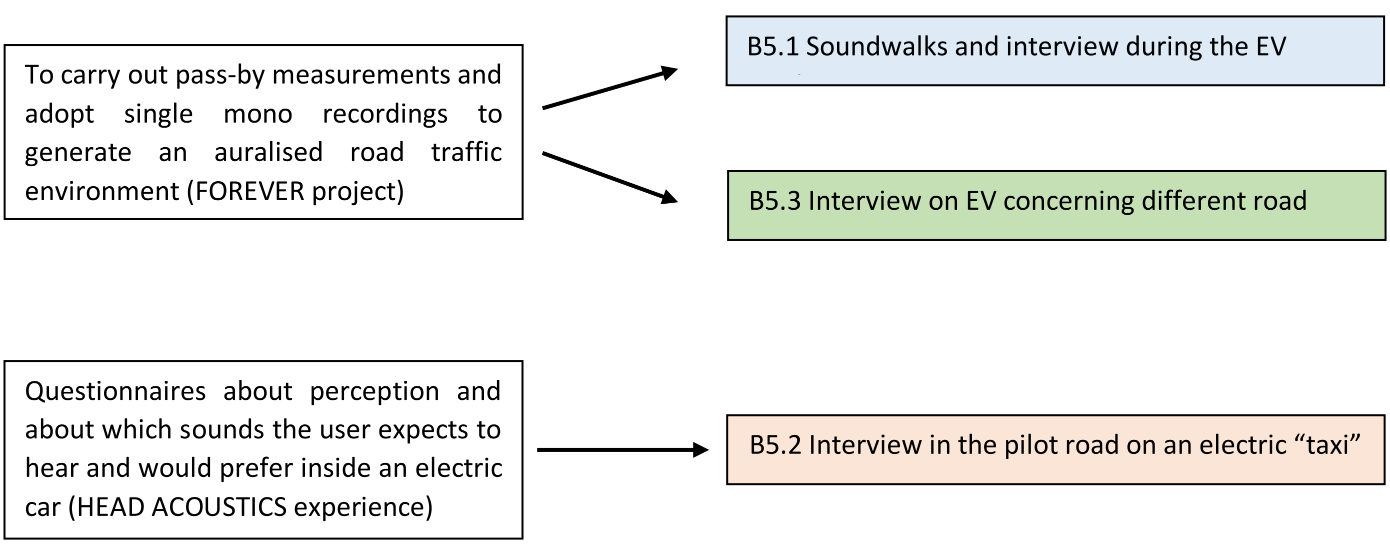


Figure 5-7 Scheme of possible state-of-the art inputs for Action B.5.

Regarding Sub-Actions B5.1, it concerns the organization of one or more soundwalks in the frame of the EV Festival. The foreseen path will also include the project pilot area. In this frame it will be possible to make participants directly listening to road traffic noise in presence of different typologies of asphalts (traditional and optimised for noise) and different typologies of vehicles (ICEV and EV). A second opportunity could be to use the pass-by measurements carried out during Action B2 in order to generate mono recordings and make people listening to them to understand their subjective perception. The same pass-by measurements could be used in the frame of Sub-Action B5.3 whose aim is to carry out an interview campaign on one or more electric bus lines; the route of which involves the passage on different types of asphalt (old, normal, optimised).
Regarding Sub-Action B5.2, it concerns the promotion in using the “LIFE E-VIA taxi” by citizens to be accompanied wherever they want in the city centre of Florence and passing through the pilot street. A “collecting” station for people who would like to participate will be established in the proximity of the Michelucci street and people, after receiving their consent, will be interviewed during the trip. Specific questions of the interview will focus on their perception of the comfort and acoustical environment while passing on the 3 different typologies of asphalt: the old one, the re-paved one without specific low-noise characteristics and the optimised one. Specific questions about the perception of noise due to EVs and ICEVs and about the differences about pavements will be also posed to taxi-drivers.
In addition, starting from the experience that HEAD Acoustics is carrying out about the “sonorisation” of electric vehicles, a section of the questionnaire to be submitted to passengers could be dedicated to questions aimed to understand which would be the most appreciated typology of sonorisation preferred by people.

As the expectations of the customers are not fixed and grounded, the frame of reference is based on previous ICEVs’ experiences. For this reason, investigations on human response turn out to be more complex and less predictable. The studies mentioned in Paragraph 5.1 present a selection of psychoacoustic parameters, which responses can be influent in sounds’ evaluation, such as Loudness, Sharpness, Roughness/Fluctuation Strength, Tonality and Prominence Ratio (PR), the latter for the detection and evaluation of prominent tones in noise emissions. Moreover, some other specific parameters have been considered: Perceived Noise Level (PNL); Tone Corrected Perceived Noise Level (PNLT) and the Effective Perceived Noise Level (EPNL).

6 EVs in noise prediction models

Noise prediction models are fundamental tools for noise impact studies or for the assessment of population exposure to environmental noise in a regulatory context. Road traffic noise is an important component due to its widely spread contribution to soundscape. Several prediction models exist either at national or international levels. In the latter case for example, CNOSSOS-EU is the European prediction method, common to all European State Members for the production of strategic noise maps. Noise prediction models generally contain a noise emission part, describing the acoustical power emitted by each source category, and a propagation part characterizing the disturbance to sound from the source to the receiver in uneven or built-up areas. This section focuses on several noise prediction models in terms of vehicle noise emission, their consideration of electric vehicles and possible extensions investigated in the literature, mainly targeting light vehicles.

6.1 Consideration of EVs in national or international prediction models

6.1.1 The European method CNOSSOS-EU

As planned from 2002 in the European Noise Directive 2002/49/EC of 25 June 2002 [105] for the production of noise maps assessing exposure to environmental noise in large urban areas and along major roads, the assessment method common to all Member States has been specified in May 2015 in Directive 2015/996 [106]. For road vehicles, the latter document structures the method principle, the vehicle classification and the noise emission equations according to driving and environmental conditions.

The CNOSSOS-EU road noise emission model considers four vehicle categories, according to their mass and axle number:

- category 1: light vehicles, ≤ 3.5 tons;
- category 2: medium-heavy vehicles, > 3.5 tons with two axles and twin tyres on rear axle;
- category 3: heavy vehicles, > 3.5 tons with three or more axles;
- category 4: powered two-wheelers.

A fifth – still open – category is left available for future needs, for instance the description of new technology vehicles like electric or hybrid vehicles.

Whatever the category, a vehicle is acoustically modelled by one single point source located 0.05 m over the road surface. Its acoustic power is composed of a propulsion noise component and a rolling noise component, both being function of the speed v and of a set of coefficients specific to each vehicle class and each octave band from 63 Hz to 8000 Hz. These coefficients correspond to the noise emission in reference conditions, including:

- a steady driving speed;
- a flat and dry road;
- an air temperature of 20°C;
- a virtual reference road surface corresponding to an average of DAC 0/11 or a SMA 0/11, between 2 and 7 years old;
- no studded tyres.

When conditions differ from the reference ones, correction terms are used.

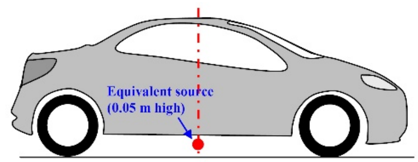


Figure 6-1 Equivalent point source for a light vehicle in CNOSSOS-EU [106].

In each octave band i, the total sound power $L_{WT,i}$ radiated by the equivalent point source is the energetic sum of a propulsion noise component $L_{WP,i}$ and a rolling noise component $L_{WR,i}$, both functions of vehicle speed v:

$$L_{WT,i}(v) = L_{WP,i}(v) \oplus L_{WR,i}(v) \tag{6.1}$$

The **rolling noise** (including also the aerodynamic noise) is defined as a logarithmic function of the speed v. In the octave band i, the sound power level $L_{WR,i}$ is formulated by:

$$L_{WR,i}(v) = A_{R,i} + B_{R,i} \log\left(\frac{v}{v_{ref}}\right) + \Delta L_{WR,i}(v) \tag{6.2}$$

where $A_{R,i}$ and $B_{R,i}$ are the rolling noise coefficients specific to the vehicle class and the octave i, and the reference speed is $v_{ref} = 70$ km/h. The term $\Delta L_{WR,i}(v)$ includes correction terms regarding road surface, acceleration, temperature and the presence of studded tyres. In particular, the road surface correction term is relevant whenever the road surface differs from the reference one. It is defined by:

$$\Delta L_{WR,road,i}(v) = \alpha_i + \beta \log\left(\frac{v}{v_{ref}}\right) \tag{6.3}$$

where the speed coefficient β is independent of frequency.

The **propulsion noise** includes the contributions from engine, exhaust, gears, air intake, etc. Its sound power level $L_{WP,i}$ is formulated by:

$$L_{WP,i}(v) = A_{P,i} + B_{P,i}\left(\frac{v - v_{ref}}{v_{ref}}\right) + \Delta L_{WP,i}(v) \tag{6.4}$$

where $A_{P,i}$ and $B_{P,i}$ are the propulsion noise coefficients specific to the vehicle class and the octave i. $\Delta L_{WP,i}(v)$ includes correction terms according to the road surface, the acceleration and the effect of road gradient. The correction term relative to the road surface is only relevant to porous surfaces and is a constant in each octave band as given by:

$$\Delta L_{WP,road,i}(v) = \min\{\alpha_i, 0\} \tag{6.5}$$

the factor α_i being also involved in the road surface correction term of the rolling noise component in Eq. (6.3).

Details on the other correction terms are not reported here since not central to the project concern, they are described in reference [106]. Default values of the rolling and propulsion coefficients result from a wide amount of measurements from European vehicles and thus refer to an average internal combustion engine (ICE) vehicle. They are listed in tables given in the text of the Directive. However, it should be noted that, after the detection of several issues, a European working group recently proposed a new coefficient list [107] and the coefficient table in the Directive is likely to be updated. Compared to the current ones, the new coefficients will have the effect of increasing the global noise emission of an average vehicle, by 2.8 dB(A) and 1.2 dB(A) for the rolling and the propulsion noise of light vehicles respectively, by 4.2 dB(A) and 2.4 dB(A) for these contributions in the two classes of heavier vehicles respectively.

According to the Directive, input data shall reflect real usage and default values are accepted only if the development of actual data is costly unreasonable [106]. Some guidelines have been formulated for defining rolling and propulsion noise coefficients, as well as additional road surface coefficients [108]. Although not much detailed, they recommend following similar approaches than those undertaken in the former project IMAGINE and in coherence with CNOSSOS propagation model. In particular, this relies on SEL pass-by levels recorded at a distance of 7.5 m from the lane centre and at a height of 1.2 m or 3.0 m. Some European countries, like the Netherlands, have chosen to use their own coefficient tables.

Investigations on electric vehicles for CNOSSOS-EU

Although mentioned in relation to the open fifth class, no description of EV noise emission is officially available up-to-date in the European prediction method. Considering the spread of electric vehicles, the issue of introducing them in the prediction model has been considered in several projects.

The CEDR project FOREVER (2013-2014), primarily focused on national roads, investigated EV noise emission on a wide speed range from 20 km/h [52]. It proposed the consideration of EVs in the CNOSSOS-EU prediction method, both by implementing a specific methodology for the determination of the model coefficients and by providing values for EV noise prediction [61]. The methodology is based on experimental data from controlled pass-by (CPB) measurements and A-weighted maximum noise levels $L_{A,max}$, and involves a numerical approach to optimise the model coefficients from the measurement results. The EV rolling noise contribution was found to be similar to those from conventional vehicles [79]. The propulsion noise turned out to be difficult to identify and separate from rolling noise, on the one hand due to the absence of a gearbox – thus linearly linking vehicle speed and engine speed – and on the other hand, because of the impossibility to disengage the clutch on EVs. While the latter prevents to perform coast-by measurement, which would have involved the sole rolling noise, the former implies the speed as unique parameter governing the two noise contributions through only one degree-of-freedom. Thus, the authors decided not to use the fifth open vehicle category of CNOSSOS-EU, but to determine EV correction coefficients applied to the basic CNOSSOS propulsion noise component as a complementary correction term to those defined in $\Delta L_{WP,i}(v)$ of Eq. (6.4). These correcting coefficients are listed in Table 6-1. Coefficients in the octaves 500-2000 Hz are quite low, resulting from the impossibility to determine them accurately while rolling noise strongly prevails in this frequency range, and reflecting that they have no actual effect on the overall noise. On most road surfaces, the propulsion noise component has a slight relative contribution to the overall noise at low speed only (see Figure 6-2 in reference conditions). Over the entire speed range, rolling noise is clearly the most significant noise contribution.

Table 6-1 Correction coefficients for the propulsion noise component of light vehicles in all-electric mode [61].

Octave (Hz)	63	125	250	500	1000	2000	4000
Correction term (dB)	-5.0	-1.7	-4.2	-15	-15	-15	13.8

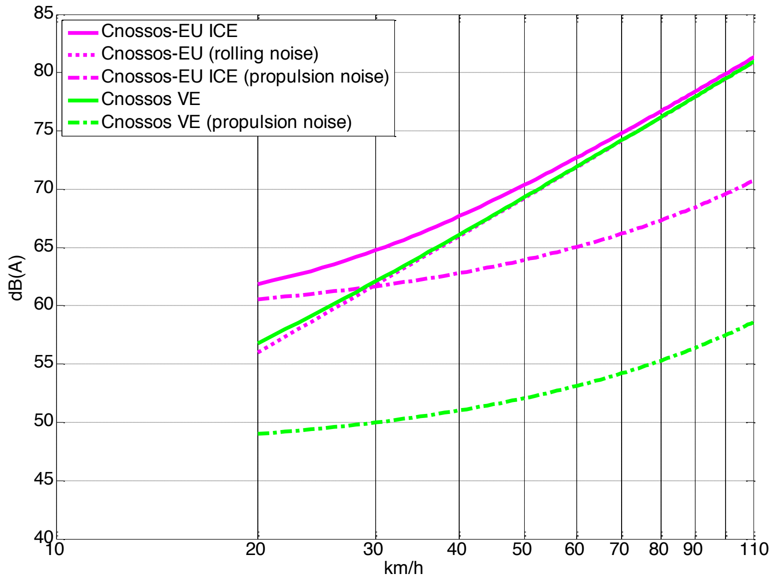


Figure 6-2 Comparison of CNOSSOS-EU (for ICE light vehicles) and the model CNOSSOS-EV determined in the project FOREVER, in overall noise levels and in reference conditions [52].

A recent study conducted by M+P for the UK government department DEFRA aimed at defining a methodology for assessing CNOSSOS model values representative of EV noise emission, making use of the open fifth vehicle category [57]. This implies the determination of the four coefficients A and B of Equations (6.2) and (6.4), in each octave band. The study does not include the practical implementation providing the numerical values of the EV coefficient. The same methodology could also be used later for updating the British national method CRTN. Several approaches have been considered for the separation of the rolling and propulsion contributions, the main challenge being the identification of the weak propulsion noise component. The use of CPX method or of indoor equipment was not considered as worthwhile for this separation regarding accuracy against cost. On the other hand, the option of simply disregarding propulsion noise would lead to underestimating EV noise emission at low speed, in particular considering the new regulation requiring AVAS systems on EVs. The chosen methodology for separating rolling noise and propulsion noise involves a numeric post-processing, based on CPB measurements with a specific microphone location and a set of EVs representative of the vehicle fleet tested on a 20-130 km/h speed range. The acoustical indicator used is the Sound Exposure Level (SEL) L_E and a measure validity is specified relatively to other traffic noise over a ±80° viewing angle and to background noise. For a given road surface and each octave band, firstly rolling noise coefficients are determined by fitting measurements at high speeds to the CNOSSOS rolling noise model only, while propulsion noise may be considered as insignificant (typically over 70 km/h). Secondly, the propulsion noise coefficients are calculated by minimising the least square error between the measured SELs and the overall CNOSSOS model, including low speeds. Finally, a frequency-dependent correction factor, inversing the transfer from the point source power level L_W to the SEL according to CNOSSOS propagation model and the measurement condition, is applied to get the set of coefficients $A_{R,i}$, $B_{R,i}$, $A_{P,i}$ and $B_{P,i}$. The study emphasises conditions for measurement validity and confidence. In a further section on the determination of road surface corrections, the authors argue that CPX measurements – relevant for type approval and labelling of road surfaces – are not suitable for deriving correcting values for noise assessment methods. For this purpose, they recommend a numeric post-processing of SPB data, based on maximum sound pressure levels (L_{Amax}) on the one hand and on the spectrum at the moment of the L_{Amax} on the other hand.

6.1.2 The Swiss model SonRoad2018

The Swiss noise emission model for traffic noise has been updated in 2018 and named sonROAD2018 [109]. It is structured like the European model CNOSSOS-EU, involving a propulsion noise component and a rolling noise similarly to Eq.(6.1), (6.2) and (6.4). Main differences concern third-octave frequency description, the vehicle category distribution (national SWISS10 classification), the introduction of a vertical directivity (specific to vehicle category and frequency) and of a random term rendering the statistical variation of traffic flow. The equation coefficients A and B, together with road surface correction coefficients, have been determined through a massive optimisation procedure concerning large quantities of vehicles observed during several pass-by measurement campaigns, on the basis of corrected sound exposure levels calculated from a restricted time interval for each valid vehicle pass-by.

Future subcategories of the SWISS10 classification should include electric and hybrid vehicles. Considering current EV noise knowledge sonROAD2018 chooses to disregard the propulsion noise component. The overall EV noise emission results from the sole rolling noise, this one being identical to that from conventional vehicles. AVAS contribution has not yet been included but should be in the future. Thus, EV noise emission does not involve new emission coefficients but a specific adaptation from conventional vehicle parameters.

6.1.3 The American model FHWA-TNM

The Federal Highway Administration of the United States provided the Traffic Noise Model (TNM©) for the prediction of highway traffic noise as early as 1998. It has recently been updated by Version 3.0 [110]. The Reference Energy Mean Emission Levels (REMELs) refer to the description of noise emission by the road vehicles.

In the traffic description, the TNM model considers four vehicle types (regardless of motorcycles): automobiles (with a gross weight less than 4.5 t), medium trucks (with two axles and six tyres), heavy trucks (with three or more axles) and buses. The vehicle noise emission is described by the maximum A-weighted sound pressure level $L_A(v)$ received on a microphone located at a 15.2 m distance from the road. In its general form, the global noise level on the sensor is controlled by three constants A, B and C such that:

$$L_A(v) = [A \log(0.6214\, v) + B] \oplus C \tag{6.6}$$

where $\oplus$ stands for the energetic summation, v is the vehicle speed in km/h[7], C concerns the engine/exhaust noise contribution and $[A \log(0.6214\, v) + B]$ the rolling noise contribution with a speed coefficient A. In addition, the spectral distribution over the frequency range is given by adjustment factors, determined by fourteen coefficients, allowing the specification of the spectrum in third-octave bands. The constants A, B, C and the fourteen spectrum constants depend on the vehicle type, the throttle condition and the road surface type. The throttle condition refers to steady speed or to full throttle driving conditions.

The vehicle noise emission is split into two sub-sources at distinct heights on the vehicle. For automobiles, these heights are 0 m and 1.5 m. The sound energy distribution among the sub-sources depends on frequency, vehicle type and throttle condition.

The database involved in the REMELs specifies the noise emission characteristics of average conventional vehicles in each category and has been updated in the latest version by the correction of a few coefficients. The speed coefficient A remained unchanged, but B and C have been modified. In any conditions for automobiles, the speed coefficient A is about 41.7. Electric vehicles are not specified in particular in the REMEL database.

[7] $(0.6214\, v)$ corresponds to the speed in miles per hour.

Investigation of REMELs for electric vehicles

In accordance with the principle of the American noise prediction model, a study estimated the REMEL curve for one electrically driven vehicle, more specifically a Chevrolet Volt which was an electric vehicle with range extender [111]. In this, the approach differs from the original REMEL curves which come from the observation of a large quantity of vehicles and represent the noise emission of an average vehicle. The Chevrolet Volt was actually a plug-in hybrid car, operating either electrically or as a series hybrid, the latter meaning that the vehicle was powered by the sole electric motor(s) whereas the engine was used as a generator to supply electricity. The full-electric operating mode was targeted in the study. A microphone position at 7.6 m, shorter than the standard position at 15.2 m, was preferred due to lower disturbance by the background noise in the context of low-noise vehicle.

In this study, results were represented in figures comparing the REMEL curves and the spectra of the electric car to the average *automobile*. The values of the constants A, B and C for the electric vehicle were not explicitly provided but one can suspect that the constant C was mostly concerned. Global levels differed significantly from conventional vehicles under 24 km/h at steady speed and under 40 km/h in full-throttle conditions. At very low steady speed (8 km/h), the electric vehicle noise spectrum was significantly reduced at all frequencies. At other speeds and when accelerating, gaps occurred mainly at low frequencies, with a limited or insignificant effect on the A-weighted global levels. Then, both models were used to compare traffic scenarios with various ratios of electric/conventional vehicles in the traffic mix.

6.1.4 The Japanese model ASJ RTN 2018

The national road noise prediction model ASJ RTN-Model of Japan was developed in the 90's and provides formulas for the noise emission of vehicles. While keeping the same form, it has been updated several times since then, so as to best represent the traffic vehicles according to their development. It has recently been upgraded with new version ASJ RTN-Model 2018 [112]. The Japanese method considers two or three vehicle categories: light vehicles (identified as passenger cars or small-sized vehicles with an overall length not larger than 4.7 m) and heavy vehicles, the latter possibly separated in medium sized and large sized vehicles.

Vehicle noise emission in each category is given by general formulas expressing the overall sound power level as a global level in dB(A) as a function of vehicle speed v, without distinction of propulsion and rolling noise contributions:

$$L_{WA}(v) = a + b \log v + \mathrm{C} \quad (6.7)$$

where C stands for correcting terms regarding road gradient and vertical directivity among other things. For each vehicle category, coefficients a and b are provided according to several driving conditions and road surface types:

- steady traffic (40 km/h < v < 140 km/h);
- non-steady traffic (10 km/h < v < 60 km/h, typically in sections with frequent acceleration and deceleration);
- deceleration section (10 km/h < v < 140 km/h, typically when arriving to a tollgate);
- acceleration section (1 km/h < v < 80 km/h, typically when leaving a tollgate);
- dense asphalt pavement;
- porous asphalt;
- gap-graded asphalt mixture.

The speed coefficient has most often a unique value for all vehicle categories in any of the foregoing conditions. For example, $b = 30$ for a steady traffic on dense asphalt concrete, in any vehicle category. The sound power spectrum in third-octave or octave bands is derived from the overall noise levels through relative power levels specific to the vehicle category and road surface.

Model revision relies on regular pass-by noise measurements allowing the updating of model parameters. In the most recent version of 2018, the overall power level of light vehicles on dense asphalt concrete has been lowered by 0.9 dB. This has been explained by the increasing number of low-noise vehicles, like hybrid and electric vehicles, in the traffic [112]. However, a further traffic decomposition in conventional and hybrid light vehicles rather identifies the new parameter values with those of conventional vehicles. Nevertheless, electrically driven vehicles are not currently separated from the others but could be in the future.

Investigation of hybrid and electric vehicles compared to ASJ RTN-Model

Electric vehicles hold an increasing part in the road vehicle market and traffic. As a preparation for the introduction of light electric vehicles in the noise prediction ASJ RTN-Model[8], a study has carried out measurements with a series of electrically driven (hybrid, electric and fuel cell) vehicles on dense asphalt concrete road surfaces [84]. Low steady speed conditions were targeted in order to point out the differences with conventional vehicles, more specifically from 15 to 40 km/h. An ICE vehicle was also measured but on a separate site from the other tests, which makes accurate comparisons difficult due to possible rolling noise differences in addition to the technology-specific propulsion noise.

The paper informs on the background noise of the test sites, which is valuable when coping with low-noise vehicles: except one day with excessive background noise, the other test conditions involved average background noise levels between 38 and 46 dB(A). For further reducing disturbance by environmental noise, the microphone was set closer than usual, at a distance of 2 m from the lane centre. On the relevant comment that the vehicles may not be considered as a point source in these conditions, the use of noise equivalent levels on a 20 m length has been preferred to the maximum sound pressure levels. However, the relation used to infer the sound power level from the equivalent level still relies on a point source assumption. Also, the assertion of possible interference between rolling noise contributions from tyres on both axles may be weak considering current tyre design. Thus, relating short distance measurement to vehicle specification as a noise source deserves deepening. The consideration of exclusively hybrid or electric cars or a mix of both conditions in the regression equations for model design is unsure, but their sound pressure levels on the Japanese dense asphalts turn out to be at least 5 dB(A) lower than the model ASJ RTN-Model 2018 for conventional cars. The trend also shows a higher speed coefficient. Some insight on AVAS noise contribution is presented, without clear effect on frequency spectra.

6.1.5 Other studies for noise prediction and noise mapping

Consideration of a model for electric vehicle noise emission has not always been motivated in the literature by the need of developing standardised noise prediction models, but sometimes as a targeted tool for a case study. For instance, the effect of introducing electric vehicles in a traffic flow on sound exposure of the population in urban areas has been considered in several studies over the last decade. These have involved simplified models of electric vehicle noise emission, either derived from existing prediction models or based on specific models. A few examples are mentioned below.

[8] Although the study also mentions CNOSSOS-EU, the derivation procedure and power level formulas relate to the context of the Japanese prediction method.

The approach used in a study by Verheijen et al. relied on the model resulting from the project IMAGINE for ICE vehicles, itself at the origin of the CNOSSOS-EU method. The authors specified the EV rolling noise as identical and the propulsion noise as 10 dB lower than those of conventional vehicles [89]. Thus, the propulsion noise spectrum remained unchanged compared with ICE cars. Environmental noise mitigation by the vehicle technology was assessed in the city of Utrecht, resulting locally in noise reduction up to 4 dB if the traffic were fully electric.

A recent study by Campello-Vicente et al. [90] leaned on the French prediction model NMPB2008, which is the method recommended in France for noise impact studies. Like most noise prediction models, NMPB2008 only considers conventional vehicles and involves a propulsion noise and a rolling noise component. For including electric vehicles, the study chose to disregard the propulsion noise component and to specify EV noise emission by the sole rolling noise [90]. The noise impact of several traffic mix scenarios of EVs/ICEVs has been investigated within an urban area of Elche (Spain). Interestingly, given the regulatory changes, it also introduced the AVAS contribution as a complementary option to the EV noise emission, so as to address its effect on the environmental noise exposure. Little detail has been provided on the characteristics of this source.

Disregarding EV propulsion noise was also the approach used by Hammer et al. in a study focusing on traffic noise in the low speed range, typically 30 km/h [60].

6.2 Connection and implication for LIFE E-VIA actions

Several noise prediction models have been developed at a national or international scale. At European level, the common assessment method CNOSSOS-EU is of particular importance, as the recommended tool for the production of strategic noise maps and, as such, is of particular concern in the LIFE E-VIA project. Concerning road traffic noise, methods include their own noise emission model describing the acoustical energy radiated by an average vehicle within a category and depending on various parameters. They generally result from a long process supported by a large amount of experimental data, ensuring representativeness in relation to the existing situation within their boundaries. They are periodically updated to follow development and changing performance of vehicles. They generally refer only to conventional vehicles and do not mention electric vehicles. Some of them have anticipated a specific category but do not take them further into account in the noise prediction, as is the case with the European method. Only the Swiss model has ruled on their quantitative inclusion in noise prediction.

Studies have been conducted, either to define a methodology for including EVs in the models or for providing exploratory EV noise emission data. Considering the current state of EV market and the still limited share in the overall vehicles in circulation, this data relies on a low number of vehicles. The methodologies for characterising their noise emission meet several main difficulties:

- The background noise may affect accuracy when considering low noise vehicles, in particular in some frequency bands and at low speed. Possible solutions include:
    - the selection of quiet test sites;
    - the systematic validation of measures against background noise, otherwise correction if possible or rejection;
    - an adaptation of the measurement procedure through a reduction of the measurement distance. However, this may invalidate the assumption of representing the vehicle as a point source and requires deepening for correct sound power estimation.

- The lack of ability to drive in neutral prevents from performing coast-by tests and thus easily extracting rolling noise, and the lack of a gearbox prevents decoupling the propulsion noise and the rolling noise contributions. Careful data post-processing may provide solutions under relevant assumptions.
- The weak contribution of propulsion noise relatively to rolling noise entails a risk of an increased estimation error of the propulsion model coefficients.

Within LIFE E-VIA project, these difficulties and solutions will have to be considered in actions involving low speed measurements and in urban context (Actions B2.1, B2.3, B4.2 and B6). In addition, microphone array measurements are planned in B2 actions for helping background noise mitigation and separation of noise source contributions in part of the frequency range.

Finally, the choice of the acoustic indicator to be used in the analysis of the CPB measurements should be considered in light of sensitivity to background noise context, considering instantaneous (L_{Amax}) against integrated indicators (SEL).

7 Conclusions

This report is a literature review on electric vehicles and their noise emission as a preparatory action A1 of the LIFE E-VIA project. It includes different aspects of the topic, structuring the outline of the study, dealing with EVs current fleet and distribution, changes in driving behaviour induced by EVs, the specificities of EV noise sources (including propulsion noise, rolling noise and AVAS), the changes in the perception of noise from EVs and the consideration of EVs in the noise predictions models. Each section has been summed up in the light of next works within implementation actions B of the LIFE E-VIA project.

Since the last years, electric vehicle market has been growing fast worldwide, especially in the European area where about 1.4 million of light vehicles were in circulation at the end of 2019, with a market share of new registrations of EVs reaching 3% in 2019. The European market is by far dominated by BEVs and PHEVs of the passenger car category, which should stay the dominant market in the next years. The international outlook for EV fleet is to reach between 15% and 30% of the global vehicle fleet by 2030. Consequently, the LIFE E-VIA project will focus on this category of vehicles within actions B1 to B7. The current BEV models dominating the total fleet in the European area helps in orienting the selection of BEVs for acoustics tests on Université Gustave Eiffel reference test track in Nantes (France) within action B2. It is advised to consider at least one model per segment in category M1 (i.e. Renault Zoe and/or BMW i3 in segment B, Nissan Leaf and/or VW e-Golf in segment C and Tesla Model 3 in segment D). An additional model shall be considered in vehicle category N1, i.e. Renault Kangoo ZE.

Several factors involve a different driving style with EVs compared to conventional ICEVs, which are the limited vehicle range, the availability of regenerative braking and different sensations (acceleration, torque, acoustical perception) arising when driving EVs. After becoming experienced, EV drivers show anticipation, use deceleration to efficiently benefit from the regenerative braking and try to drive economically by favouring a constant speed as far as possible. EV drivers have a perception of the vehicle, either from technical performance (acceleration ability and torque availability) or from acoustical feedback, which differs from conventional vehicles. This may affect their driving behaviour in different ways, often by driving more smoothly with effects on speed, acceleration/deceleration rates and lengths, but also sometimes by more aggressive driving schemes noticed with fleet users or users having powerful EVs. The ongoing traffic conditions and vehicle range certainly play a central role in the adoption of one or the other attitude. Smooth driving is favourable to propulsion noise and rolling noise reduction, while aggressive driving leads to increase of noise during accelerating and decelerating driving conditions, counteracting the potential impact of EVs on road traffic noise reduction. Therefore, the specificities of driving behaviour shall be considered in the characterisation of tyre/road and vehicle noise emission within implementation actions B2 and B4 of the LIFE E-VIA project. In addition to steady-speed driving conditions, acceleration and deceleration situations shall be performed, thus providing noise emission skills in relation with the diversified performance of the tested electric vehicles. Deceleration tests should include regenerative braking situations without frictional brakes as far as possible. Acceleration tests are also planned in sub-action B2.4 dealing with optimisation of EV tyres.

Existing studies on noise source emission of EVs have shown that for this type of vehicle tyre/road noise dominates propulsion noise for a speed of 30 km/h and above. Thus, in the perspective of growing electric mobility in urban area, the choice of low noise tyres and quiet road surface is essential for noise reduction. This is one of the main objectives of the LIFE E-VIA project through the implementation of an acoustically optimised solution of road surface and tyres for EVs. Most of the time, the literature review points out a lack of information on tyres, pavement types and/or background noise of test sites, leading to some uncertainties in the analysis of vehicle noise emission from pass-by measurements. Moreover, a main difficulty in existing studies is the separation of noise sources at low speeds, i.e. propulsion noise and rolling noise, due to the fact that the driveline is not the only varying parameter when comparing electric and ICE test vehicles. In action B2 of LIFE E-VIA, measurement campaigns will be performed on the reference test track of Université Gustave Eiffel in Nantes (France) which benefits of a relatively low background noise (about 40 dB(A)). Six existing road surfaces with fully characterised properties will be considered for noise measurements (pass-by and close-proximity) of different EV models in sub-action B2.1. In sub-action B2.3, a prototype of low noise road surface developed during the project will be built on the same site, then fully characterised from an acoustical point of view and used for tyre optimisation within sub-action B2.4. Regarding separation of noise sources at low speed, pass-by tests will be performed for two Renault Kangoo with strictly identical properties (bodywork and tyres), but with different motor type (i.e. electric or ICE), in order to avoid a bias in rolling noise emission. Additionally, the different EV models will be systematically measured with a microphone array when rolling on a smooth road surface conforming ISO 10844. This kind of smooth road surface should minimize the rolling noise contribution and will support the separation of noise sources. This methodology will lead to important information regarding rolling noise and optimisation of tyre/road interaction, for optimal mix and tyre developments in actions B1 and B2.4/B7 respectively.

Regarding noise perception, the number of EVs is increasing nowadays, involving positive effects, compared to ICEVs, such as the reduction of noise emissions. In order to make vehicles noticeable, possible solutions may provide non-acoustic or acoustic measures addressed to drivers or pedestrians. Thus, it is important to raise people's awareness of noise pollution and correlated health effects. Therefore, investigations on human response, including soundwalks and interviews, are crucial for a wider perspective. According to FOREVER project's method, Vie en.ro.se' aim for sub-action B5.1 is to make participants listen to road traffic noise in presence of different typologies of asphalts and different typologies of vehicles (ICEV and EV) and to distribute related questionnaires (sub-action B5.3). Regarding sub-action B5.2, people are asked to be the passengers of an electric "taxi" in the pilot road. As suggested by Head Acoustics experience, an interview will be conducted. Specific questions will focus on the perception of the comfort and acoustical environment while passing on three different typologies of asphalt and on the perception of the noise due to EVs and ICEVs.

Several road traffic noise prediction models have been developed at a national or international scale, but the majority only refer to conventional vehicles and do not mention electric vehicles. Some of them have anticipated a specific category, but do not yet take EVs further into account in the noise prediction, as is the case with the European method CNOSSOS-EU. Studies have been conducted, either to define a methodology for including EVs in the models or for providing exploratory EV noise emission data. Considering the current state of EV market and the limited share of EVs in the overall fleet, these data rely on a low number of vehicles. The methodologies for characterising noise emission of EVs encounter several difficulties, which are pollution of low noise vehicles by background noise in some frequency bands and at low speed, the impossibility to drive EV in neutral preventing coast-by tests and proper extraction of rolling noise, and finally the weak contribution of propulsion noise relatively to rolling noise, which entails a risk of an increased estimation error of the propulsion model coefficients. Within the LIFE E-VIA project, these difficulties and solutions will have to be considered in actions involving low speed measurements in urban context (Actions B2.1, B2.3, B4.2 and B6). Finally, the choice of the acoustical indicator to be used in the analysis of the CPB measurements should also be considered in light of sensitivity to background noise context, considering instantaneous (L_{Amax}) against integrated indicators (SEL).

To conclude, the literature review performed within the preparatory action A1, together with the companion preparatory actions A2 and A3, respectively on "Quiet pavement technologies and their performance over time" and "Tyre role in the new context of EV and ICEV", provides solid bases and methodological recommendations regarding the implementation of the LIFE E-VIA project, specifically for the optimisation of tyre/road noise reduction in the context of a growing electric vehicle fleet in urban area.

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