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## Noise emission of electric and hybrid electric vehicles : deliverable FOREVER (n° Forever WP2\_D2-1-V4)

Marie-Agnès Pallas, John Kennedy, Ian Walker, Roger Chatagnon, Michel Berengier, Joël Lelong

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## **CEDR Transnational Road Research Programme Call 2012: Noise**

Funded by Belgium/Flanders, Germany,  
Ireland, Norway, Sweden, United Kingdom



# **FOREVER**

## **Noise emission of electric and hybrid electric vehicles**

Deliverable FOREVER\_WP2\_D2-1\_v4  
April 2015



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# CEDR Call2012: Noise FOREVER Future Operational impacts of Electric Vehicles on European Roads

## Noise emission of electric and hybrid electric vehicles

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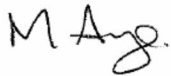
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## Executive summary

### Context

Electric and hybrid-electric vehicles are often referred to as quiet vehicles, comparatively to conventional internal combustion engine (ICE) vehicles, although this assertion might be tempered in some cases. On one hand some low noise ICE vehicles can be encountered in the fleet in circulation. On the other hand the driving conditions can affect the powertrain and the rolling noise contribution, thus impacting the global noise emission differently depending on vehicle categories.

The electric and hybrid powertrain technologies are mostly employed on light vehicles, either for the carriage of passengers or for goods, but a more recent breakthrough of electromobility can also be observed in heavier vehicles, such as delivery trucks or buses. At first, these new vehicle types were mainly developed for urban situations, primarily for their qualities concerning air pollution reduction. However, due to the improvement of their electric range, they can also be encountered on national road networks.

The character of electric vehicle noise has the potential to be different from traditional internal combustion vehicle noise in terms of features such as directionality, frequency content and sound pressure level. The data available from the standard pass-by tests has been analysed and compiled into a noise database of vehicles appropriate for use in subjective participant studies. The aim of these studies was to investigate the changes in the subject responses of human listeners to EV noise from national routes.

### Description of the work

The project FOREVER aims primarily to provide data and information on the potential future noise impacts of electric vehicles on national roads. Work Package 2 (WP2) of the project is intended to identify the noise emission levels from electric and hybrid-electric vehicles. This involves a review of the state-of-the-art in vehicle noise evaluation methods and how these can be applied to electric vehicles, considering the issue from the perspective of operation in controlled conditions rather than just strict type-approval conditions. The study includes practical testing carried out on a range of electric and hybrid-electric vehicles to determine noise emission levels. The objective is to derive input data for use within noise prediction models such as CNOSSOS-EU. Two vehicle categories, light<sup>1</sup> and medium heavy<sup>2</sup> vehicles, are considered in the study which focuses entirely on external noise.

The noise impacts from the perspective of human listeners, e.g. communities near national road ways, were also considered through a series of subjective participant trials. These studies investigated how the change in the character of noise emission of electric vehicles is perceived by human listeners. A system of perceptual dimensions similar to past research (Giudice, 2010) was used to assess the noise emission of electric vehicles.

The particular topic of the noise impact assessment on sound alerting systems, originally planned in the programme of WP2, could not be carried out since these alert systems are not standard equipment on low-noise vehicles yet and were not available on the vehicles tested in WP2.

<sup>1</sup> Vehicles with a gross vehicle weight  $\leq 3.5$  t.

<sup>2</sup> Vehicles with two axles and a gross vehicle weight larger than 3.5 t.



## Results on the noise emission levels from EVs and HEVs

A literature review has been conducted on the noise emission from electric vehicles (EVs) and hybrid electric vehicles (HEVs), which showed that:

- The studies motivated by perceptive outcomes carry out specific experiments, generally out of any standard procedure, only occasionally with some common features. Consequently, quantitative results cannot be strictly compared from one study to the other.
- The studies motivated by noise impact outcomes for dwellers rely either on on-board measurements or on roadside measurements. Most studies involve measurements with roadside microphones at standard position and pass-by procedures complying with international standards. These standard specifications are extended to pass-bys performed over a wider range of operating and speed conditions. Some studies complete the previous standard approach with microphone array measurements.
- One crucial point for the measurement of the noise emission from quiet vehicles is the background noise, which may limit the validity of the noise measures at low vehicle speed and is still more critical in some frequency bands. Even situations usually considered as quiet might be too noisy in this context.
- At high speeds all studies agree and assert that all vehicles behave similarly, since rolling noise is the dominating source. At constant low speed, most authors conclude that EVs and HEVs, the latter as far as no engine is working, are quieter than ICE cars. However, other studies show that on average there is no substantial difference between EVs/HEVs and ICE cars on the whole speed range. Results are also mixed when dealing with noise increase under acceleration.
- Few studies are available on hybrid and electric heavy vehicles. Studies involving either a heavy parallel hybrid truck or buses showed that a significant noise breakthrough occurred between the hybrid and electric modes, more clearly than between conventional ICE and hybrid vehicles, although the hybrid advantage may depend on the type of hybridization. Braking situations, activating the energy recovery system, can increase vehicle noise emission when compared with steady speed.

Experimental tests were undertaken by IFSTTAR, with the measurement of the noise emission of a small electric car, a larger hybrid car and an electric truck at pass-by, involving microphones at the standard position (distance 7.5 m) and a microphone array. The results showed that:

- The EVs and HEVs generally use either a direct transmission or an automated gearbox and the transmission cannot be disengaged. The propulsion noise component and the rolling noise component cannot be separated from common pass-by noise measurement without complementary information. The use of indoor test condition and/or simultaneous on-board instrumentation should help to focus on the propulsion noise component.
- At steady speed the global A-weighted noise pressure level at vehicle pass-by increases linearly with  $\log(\text{speed})$ , for all vehicles in all-electric mode. The middle frequency bands are dominating over most of the speed range. A deceleration (without braking) does not change much the emitted noise if the deceleration rate is

moderate, but the noise was observed to increase significantly if the energy recovery is strong, with or without braking.

- At steady speed with the hybrid passenger car, global noise emission differences between the electric and the hybrid mode occur up to 40 km/h. There is no difference over 40 km/h. The noise level in braking situation is similar to moderate acceleration.

In order to set out an appraisal on the noise emission of EVs and HEVs, appropriate data available by the project partners have been collected. Only measures at steady speed providing noise levels at 7.5 m from the track centre have been considered. They have been compared with the sound emission model provided in CNOSSOS-EU. The results are indicative, due to the restricted number of vehicles available in the data collection. They showed that:

- Concerning light vehicles in electric mode: the global noise emitted by all vehicles follows a linear trend with  $\log(\text{speed})$ . The difference between the quietest and the noisiest vehicle is 4.5 dB(A) at any speed of the range 20-50 km/h. The noise increase is not linear in some frequency bands. In its present form, CNOSSOS-EU overestimates propulsion noise emission from light electric vehicles in all octave bands and, consequently, in global levels. A corrected version for EVs is required if a prediction of the noise impact from a traffic flow including EVs is needed.
- Concerning light vehicles in hybrid mode, the noise emitted by the few hybrid vehicles in the data collection exhibits a quite common behaviour.
- Concerning the medium heavy vehicles, the analysis concerns few vehicles, evaluated on one test site. For the vehicles in all-electric mode, large noise level differences are noticed between vehicles of dissimilar GVW and tyre size. For the vehicles in hybrid mode, the type of hybridization might be a key parameter for the powertrain noise contribution.
- Concerning CNOSSOS-EU for medium heavy ICE vehicles, the characteristics of the prediction model raises question, about the weight granted to propulsion noise over the whole speed range relatively to rolling noise. In addition, test results available by IFSTTAR with ICE vehicles are not consistent with this prediction, as well as other results published in the literature. Further investigation is needed on ICE prior to considering any correction to CNOSSOS-EU for electric and hybrid vehicles in this category.

An adaptation of CNOSSOS-EU has been proposed for light EVs and HEVs. *Since the number of vehicles available in the analysis was limited, the results given in the report should be taken as indicative and values provided represent a first step toward the specification of electric vehicles in CNOSSOS-EU. Confirmation by complementary studies is necessary.*

The specifications for a corrected version of CNOSSOS-EU for light electric vehicles are:

- The approach is based on constant correction terms to be applied on the propulsion noise component given in CNOSSOS-EU for ICE cars, as long as another equation, physically consistent with the actual propulsion noise from electric vehicles, is not available.

- The values of these correction terms have been determined and are given in each octave band from 125 Hz to 4000 Hz.
- Conclusions on rolling noise are drawn and reported in WP3 of FOREVER (Gasparoni, 2014).
- In global levels, the weight of the propulsion noise component in the total noise from EVs remains small (if not negligible) in the total noise, which is not systematically true in some octave bands.

For light hybrid vehicles operating in hybrid mode, no correction is necessary and CNOSSOS-EU specifications are recommended. When operated in electric mode, hybrid vehicles behave like full-electric vehicles.

### **Results on the perceptive study on EVs**

The character of electric vehicle noise has the potential to be different from traditional internal combustion vehicle noise in terms of features such as directionality, frequency content and sound pressure level. The data available from the standard pass-by tests has been analysed and compiled into a noise database of vehicles appropriate for use in subjective participant studies. The aim of these studies is to investigate the changes in the subject responses of human listeners to EV noise from national routes.

A key aim of the research has been to develop a controllable model of various road traffic mixes on a rational route way. Using this approach it has been possible to investigate the effect of increasing percentages of electric vehicles as a source of the noise emission on subjective responses to the noise.

As a start point for this process the standard pass-by measurement data was utilised. The challenge addressed and met in the FOREVER project was therefore to use these single mono recordings to generate an auralised road traffic environment in a rigorous and repeatable way. This represents a novel approach making use of the ISO standard measurement procedures to generate auralizations of road environments. This approach could be used as a dissemination tool or in further research into community responses to traffic noise exposure. Within the project various road traffic mixes of ICs and EVs were produced. A road profile corresponding to a national route way was used and the percentage of EVs was then varied from 0% to 20%, 40%, 60% 80% and 100%.

Research on the subjective response of participants to these various vehicle mixes suggests quite clearly that a widespread transition from conventional to electric vehicles on national roads would not harm the subjective experience of people near those roads, and indeed would likely improve that experience.

# 1 Introduction

Electric and hybrid-electric vehicles are often referred to as quiet vehicles, comparatively to conventional internal combustion engines (ICE) vehicles, although this assertion might be tempered in some cases. On one hand some low noise ICE vehicles can be encountered in the fleet in circulation. On the other hand the driving conditions can affect the powertrain and the rolling noise contribution, thus impacting the global noise emission differently depending on vehicle categories.

The electric and hybrid powertrain technologies are mostly employed on light vehicles, either for the carriage of passengers or for goods, but a more recent breakthrough of electromobility can also be observed in heavier vehicles, such as delivery trucks or buses. At first, these new vehicle types were mainly developed for urban situations, primarily for their qualities concerning air pollution reduction. However, due to the improvement of their electric range, they can also be encountered on national road networks.

The project FOREVER aims primarily to provide data and information on the potential future noise impacts of electric vehicles on national roads. Work Package 2 (WP2) of the project is intended to identify the noise emission levels from electric and hybrid-electric vehicles. This involves a review of the state-of-the-art in vehicle noise evaluation methods and how these can be applied to electric vehicles, considering the issue from the perspective of operation in controlled conditions rather than just strict type-approval conditions. The study includes practical testing carried out on a range of electric and hybrid-electric vehicles to determine noise emission levels. The objective is to derive input data for use within noise prediction models such as CNOSSOS-EU. Two vehicle categories, light<sup>3</sup> and medium heavy<sup>4</sup> vehicles, are considered in the study which focuses entirely on external noise<sup>5</sup>.

The noise impacts from the perspective of other road users, e.g. other drivers, are also considered through a series of subjective participant trials. These studies investigate how the change in the character of noise emission of electric vehicles is perceived by human listeners. A system of perceptual dimensions similar to past research (Giudice, 2010) is used to assess the noise emission of electric vehicles.

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 (Hanna, 2009). Others pointed out that vehicle accident statistics are still insufficient or incomplete and cannot provide a reliable outcome (JASIC, 2009)(Verheijen, 2010) (Sandberg, 2010)(Morgan, 2011). 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 (for example (Garay-Vega, 2010)(Wall Emerson, 2011)). That is why some nations or country unions are preparing guidelines/requirements/regulations for Acoustic Vehicle Alerting Systems (AVAS) to be installed on hybrid electric and electric vehicles. Car manufacturers are also working to introduce alert sounds to warn vulnerable road users. If these additional sounds have a positive impact on safety, can they inversely produce a negative effect on the environment? This particular topic, originally planned in the programme of WP2, could not be carried out

<sup>3</sup> Vehicles with a gross vehicle weight  $\leq 3.5$  t.

<sup>4</sup> Vehicles with two axles and a gross vehicle weight larger than 3.5 t.

<sup>5</sup> Internal noise, relating to passenger comfort and sound quality inside vehicles, is outside the scope of this study.

since these alert systems are not standard equipment on low-noise vehicles yet and were not available on the vehicles tested in WP2.

## **1.1 Content and methodology for the identification of noise emission levels from electric and hybrid-electric vehicles**

For gasoline and diesel engine vehicles, various measurement methods relating to vehicle noise emission have been investigated in the past and some of them have been or are being standardized. For example, pass-by and close proximity methods (ISO 362-1, 2007), (ISO 362-2, 2009), (ISO/CD 362-3), (EN ISO 11819-1, 2002), (ISO/CD 11819-2). Other methods, involving microphone arrays and array processing, have been implemented to focus on individual noise sources. All of these methods can be employed to determine the main noise emission characteristics in the various vehicle categories (passenger cars, vans, medium and heavy trucks, buses, etc.), particularly in terms of powertrain noise and tyre-road noise to be introduced in the predicting models which are used, for instance, to build noise maps. Finally, other procedures have been developed more recently, specifically for the assessment of low-noise vehicles, in order to ensure a minimum noise level for safety purpose (SAEJ2889-1, 2012)(ISO/CD 16254). These assessment methods are detailed in the state-of-the-art section of this report. When originally developed for combustion engine vehicles, their adequacy to electric and hybrid-electric vehicles is checked.

The noise emission from several electric and hybrid-electric vehicles has been measured by IFSTTAR within the Work Package period, considering various driving situations: constant speed, moderate or full acceleration, deceleration and braking. It includes standard measurement of pass-by events and noise source description using a microphone array. Similar data already available by partners has been collected to widen the project dataset. This vehicle sample is used to provide noise emission description in various vehicle categories. Global and frequency levels are considered.

The direct effects of electric and hybrid-electric vehicles on the environment in the vicinity of dwellings built along national roads will be assessed in Work Package 4 of FOREVER, on the basis of equivalent sound pressure levels (European noise indicator  $L_{den}$ ). To this end, the European CNOSSOS-EU prediction model can be used. However, electric and hybrid-electric vehicles are not considered in its present version. Thus, as a first step, a global description of the method implemented in the model is proposed in the present report, emphasizing particularly the parameters which could be adapted or modified in order to take into account the specific characteristics of electric and hybrid vehicles. Finally, a proposal is formulated to take EVs and HEVs into account within CNOSSOS-EU for light vehicles at steady speed. The approach followed to provide this proposal is detailed, including motivations and limitations. A specific investigation on medium heavy vehicles is also carried out.

## **1.2 Content and methodology of the perception study on electric vehicle noise**

The character of electric vehicle noise has the potential to be different from traditional internal combustion vehicle noise in terms of features such as directionality, frequency content and sound pressure level. The data available from the standard pass-by tests has been analysed and compiled into a noise database of vehicles appropriate for use in subjective participant studies. These studies investigate how the change in the character of

noise emission from a national route due to the addition of electric vehicles might be perceived by residential communities.

The resources available for this element of the project research are relatively small. Due to the nature of the partners involved in this task, namely Trinity College Dublin and University of Bath, it was felt that increased benefit and resources could be found by integrating the work of the FOREVER project with graduate level research projects on going in both universities. This enabled the partners to draw on a greater pool of resources than afforded by the original project budget. TCD's main role in WP2 was the development of a rigorous real world auralization of road traffic environments which include electric vehicles. This dataset was produced and then provided to University of Bath for use in a participant study.

The auralizations generated from the experimental measurements were used to assess how people living close to national roads might subjectively respond to increases in the proportion of EVs in passing traffic. Auralizations of road traffic noise were produced that include 0%, 20%, 40%, 60%, 80% and 100% EVs in the traffic mix. As well as the 6 different mixes of conventional and EV noise described above, participants also heard bandpass-filtered versions of each to help identify which (if any) frequency components of the traffic sounds contribute to differences in the subjective perception of traffic with different amounts of EV component.

The extent to which these responses differed as a function the proportion of EVs in each auralization revealed the extent to which the presence of EV sound increases or decreases the subjective noise pollution of traffic on national roads. The data from the bandpass-filtered versions helped identify the frequency components most likely responsible for changes in subjective experience and annoyance. These data thereby allowed us to draw conclusions for the potential impact of electric vehicle noise emission on current community noise legislation and, in the case of the data from the filtered stimuli, potentially help with the development of physical countermeasures to the disturbance caused by traffic noise with increased EV use.

### **1.3 Structure of the report**

The report is structured as follows:

- Section 2 is a detailed state-of-the-art on measurement methods of vehicle noise emission and on the vehicle models used in several road traffic noise prediction models, aiming at providing information to the subsequent project tasks and work packages:
  - Subsection 2.1 presents standard methods used to describe the rolling noise and the powertrain noise of conventional vehicles and considers their interest toward electric and hybrid electric vehicles.
  - Subsection 2.2 presents the microphone array methodology which can be used to characterize vehicle noise sources at vehicle pass-by.
  - Subsection 2.3 reports on noise assessment approaches specific to low noise vehicles.
  - Subsection 2.4 sums up how individual vehicles are described in several national or transnational noise assessment methods.

- Section 3 is a review of literature related to exterior noise emission levels from electric and hybrid electric vehicles.
- Section 4 reports on the practical trials performed with electric and hybrid electric vehicles within the project FOREVER, in order to assess their noise emission in various operating conditions. It also describes similar data already available by partners, and draws overall conclusions in vehicle categories (light and medium heavy vehicles).
- Section 5 proposes a correction to be used in CNOSSOS-EU as a noise emission model for describing the light electric vehicles in environmental noise impact studies. It also includes comments on hybrid vehicles.
- Section 6 is dedicated to medium heavy vehicles. It investigates the adequacy of CNOSSOS-EU for ICE vehicles in this category and the implications for HEVs and EVs prediction models.
- Section 7 outlines the procedure for the generation of road traffic auralizations with various mixes of ICs and EVs. It also outlines the participant study investigating the subjective differences in response to these environments.

## 2 Review of measurement methods and models of vehicle noise emission

In the prediction models used to assess the noise impact from road infrastructures, the noise emitted by the road traffic basically relies on a generic acoustical description of the individual vehicles, itself often separated in a powertrain noise component and a rolling noise component. Both of them are generally estimated from a large number of vehicles by implementing specific measurement methods, which are reviewed in the first part of this section. Then, the emission models of individual vehicles available in various noise assessment methods is surveyed and compared, as a preliminary of WP tasks on EVs and HEVs.

### 2.1 Measurement methods: identification of the powertrain and tyre-road noise contributions

#### 2.1.1 Contribution of the tyre-road noise: standards based on pass-by measurements

In the European project SILENCE, subproject F was devoted to road surfaces as a key element for the generation of road traffic noise. It included a review on measurement methods used to assess the contribution of rolling noise. The subsection on tyre-road noise measurement of the present report is based on information provided in the report F.D13 provided in the European project SILENCE (Haider, 2006), complemented by comments on their use with EVs and HEVs.

##### 2.1.1.1 Statistical Pass-By Method (SPB)

This method is covered by the ISO 11819-1 standard (ISO, 2002). The purpose of this standard is to evaluate different road surface types by measuring traffic noise for various compositions of road traffic. The method is applicable to traffic travelling at constant speed, and is used for two main purposes:

- to classify road surfaces according to their influence on traffic noise
- to evaluate the influence on traffic noise of road surfaces at particular sites.

Measurements must be performed under controlled weather conditions, and the main meteorological characteristics have to be measured within specified accuracy. This condition is also required in the other standard methods presented in the next paragraphs.

The measurement (at a specified roadside location) of the maximum A-weighted sound pressure levels ( $L_{Amax}$ ) and of the vehicle speeds is performed on a significant number of individual vehicle pass-bys. The following vehicle categories are considered to be sufficient for the description of the noise characteristics of road surfaces:

- Category 1 : Passenger cars (excluding other light vehicles)
- Category 2a : Dual-axle heavy vehicles
- Category 2b : Multi-axle heavy vehicles

Different speed ranges are defined with respect to the categories of roads on which the traffic flows. These categories are usually associated with some areas (interurban, urban, suburban, rural ...). Three road speed categories are defined by the ISO 11819-1 standard:



- low road speed category: conditions which relate to traffic operating at an average speed of 45 km/h to 64 km/h
- medium road speed category: conditions which relate to traffic operating at an average speed of 65 km/h to 99 km/h
- high road speed category: conditions which relate to cars operating at an average speed of 100 km/h or more.

A reference speed is given for each of the speed ranges and vehicle categories. A minimum number of measured vehicles are required to reduce random errors:

- Category 1 : min. 100
- Category 2a : min. 30
- Category 2b : min. 30
- Category 2a and 2b together : min. 80

For each vehicle category, a regression line is calculated on the maximum A-weighted sound pressure levels versus the logarithm of speed. From this regression line, the average maximum A-weighted sound pressure level ( $L_{veh}$ ) is determined at the reference speed. If a mixed traffic flow is measured, a Statistical Pass-By Index (SPBI) can be calculated in order to aggregate the  $L_{veh}$  of the different vehicle categories. This index, not suitable for determining actual traffic noise levels, is calculated as follows:

$$SPBI(dB) = 10 \log \left[ W_1 10^{0.1L_1} + W_{2a} \left( \frac{v_1}{v_{2a}} \right) 10^{0.1L_{2a}} + W_{2b} \left( \frac{v_1}{v_{2b}} \right) 10^{0.1L_{2b}} \right] \quad (1)$$

where

- $L_1, L_{2a}, L_{2b}$  : vehicle sound levels for vehicle categories 1, 2a and 2b
- $W_1, W_2$  and  $W_{2b}$  : weighting factors which are equivalent to the assumed proportions of vehicles categories in the traffic. The values of these factors are defined in (ISO, 2002)
- $v_1, v_{2a}, v_{2b}$  : reference speeds of individual vehicle categories (also defined in (ISO, 2002))

The SPB method is widely used for road surface classification and has the following properties, as listed in (Haider, 2006):

Advantages:

- Measurement of complete noise output of road vehicles
- Realistic listening situation
- Includes vehicles of all types
- Allows for weighting of vehicle categories
- Large statistical sample
- Accuracy, reproducibility, repeatability

Disadvantages:

- SPB is a spot method
- Stringent conditions on surface and surroundings

- Difficulty to apply in case of high traffic density or, conversely, too low traffic in some vehicle categories
- Reference speed vs. covered speed range
- Practicability and cost-effectiveness

### 2.1.1.2 The SPB method using a Backing Board

This part of ISO 11819 standard, described by the ISO DPAS 11819-4 (ISO, 2012), describes the Backing Board method (BB), which is a modified version of the SPB method using a microphone mounted on a backing board instead of a microphone in usual free-field conditions (see Figure 1). In order to limit the diffraction effects, the microphone is not situated at the centre of the backing board, but for example in the lower right corner of the board (33 cm from the right edge and 23 cm from the lower edge in the case of the board illustrated by Figure 1).

The measuring principle is the same as in Part 1 of ISO 11819, the BB method is suitable for measurements performed in an urban built-up environment or in the presence of reflective obstacles, such as safety barriers, noise barriers, embankments... The noise coming from the front is reflected by the backing board in a controlled way so that it can be taken into account by applying a correction to the measured value (a doubling of the sound pressure caused by the backing board increases the A-weighted sound pressure level by 6 dB).

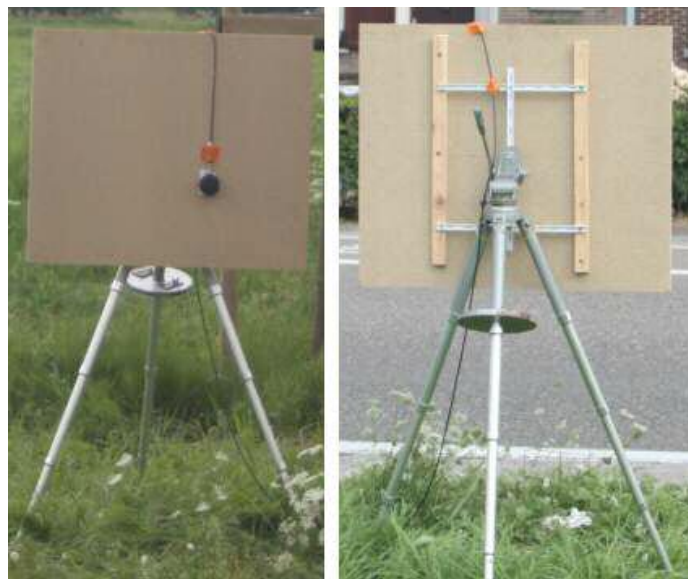


Figure 1: ISO 11819-4 – Example of backing board. [source IFSTTAR]

### 2.1.1.3 Controlled Pass-By Method (CPB)

The CPB method (AFNOR, 2000), which can be considered as a variant of the SPB method, is used when the requirements of the SPB are not fulfilled, especially:

- when the number of passing vehicles in one of the categories is too low (in particular, test installations of road surfaces not open to the general traffic)
- when the vehicle pass-bys cannot be easily separated.

Pass-bys at selected speeds are carried out using test vehicles and test drivers in order to determine the regression equation centred at the required reference speed.

Compared to SPB method, the CPB method offers the following properties (Haider, 2006):

Advantages:

- Complete control over vehicle sample
- Controlled speed, driving and surface conditions
- Faster and more cost-effective than SPB method

Disadvantages:

- representative test vehicles required
- test sites preferred

### **2.1.2 Contribution of the tyre-road noise: the close-proximity method (CPX method)**

The CPX method is cited below for completeness, although it is not implemented in the work achieved in the Forever project. In the experimental tasks, only the noise emitted at vehicle pass-by is investigated.

The CPX method is an on-board measurement method, sharing the same objectives as the SPB but with the specific intent to complement it in some limitations. In particular it gives the possibility to characterize road surfaces at almost any arbitrary site and over longer distances, checking the longitudinal and lateral homogeneity of road sections (ISO, 2013-1). It uses a test vehicle, either self-powered or towed, equipped with reference tyres<sup>6</sup> and at least two microphones located close to the tyre/road interface. Average third-octave and global A-weighted sound pressure levels are provided over 20 m long road segments. The vehicle speed is recorded and corrections are used to provide noise levels at nominated reference speeds. Then, further averaging may be performed over several road segments and several runs. Finally, the standard CPX level is provided for a given reference tyre ( $t=P$  or  $H$ ) and a reference speed ( $V$ ):

$$\text{For light vehicles} : CPXP_V = Lcp_{P,V} \quad (2)$$

$$\text{For heavy vehicles} : CPXH_V = Lcp_{H,V} \quad (3)$$

$CPXP$  and  $CPXH$  may be combined to give a composite CPX level for a mixed traffic of light and heavy vehicles at the reference speed  $V$ , referred to as the CPX Index (CPXI), expressed as:

$$CPXI_V = 0,5 \cdot CPXP_V + 0,5 \cdot CPXH_V \quad (4)$$

In terms of advantages and disadvantages, the main characteristics of the CPX method are the following (Haider, 2006):

Advantages:

- possibility to perform measurements over large distances
- good immunity with respect to background noise and reflections
- small traffic dependence
- good practicability

<sup>6</sup> The reference tyres will be described by the ISO 11819-3 standard presently in discussion.

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Disadvantages:

- method only designed for tyre/road noise identification
- not particularly adapted for heavy vehicle tyre/road noise identification
- does not account for propagation effects
- representativeness of test tyres
- good reproducibility requires a certification of the CPX equipment.

### **2.1.3 Comparison of the properties of ISO 11819-1/2/4 and CPB methods**

The ISO 11819-1/2/4 standards intend to assess rolling noise. Therefore the use of quiet vehicles (from the point of view of the emitted power unit noise) is undoubtedly an advantage, especially in the following applications:

- when the ISO 11819-1/4 are used to characterize the road surfaces at low speed (for instance in urban or suburban areas)
- when the ISO 11819-2 is used with a self-powered vehicle. The use of a quiet vehicle can avoid contaminating the measurements with power-unit noise.

Table 1 summarizes the advantages/disadvantages of the ISO 11819-1/2/4 standards and CPB method for different criterions (Haider, 2006), when conventional vehicles with internal combustion engine (ICE), electric powered (EV) and hybrid/electric (HEV) vehicles are investigated.

Table 1: Extension of the table displayed in the SILENCE report (Haider, 2006) to EV and HEV vehicles

Criterion	NF EN ISO 11819-1 (SPB)			ISO/DIS 11819-2 (CPX)			ISO/PAS 11819-4 (BB)			CPB		
	ICE	HEV	EV	ICE	HEV	EV	ICE	HEV	EV	ICE	HEV	EV
Speed range 30-130 km/h covered	++	++	++	++	++	++	++	++	++	++	++	++
Sensitivity to engine noise influence	++	++(H) --(E)	--	-	-(H) --(E)	--	++	++(H) --(E)	--	++	++(H) --(E)	--
Resistance to background noise	--	--	--	-	-	-	--	--	--	--	--	--
Usable for urban traffic composition	++	++	++	-	-	-	++	++	++	++	++	++
Accounts for heavy trucks noise	++	++	++	--	--	--	++	++	++	+	+	+
Short homogeneous test sections possible	++	++	++	--	--	--	++	++	++	++	++	++
Length of measured road section	--	--	--	++	++	++	--	--	--	--	--	--
Time consumption	++	++	++	-	-	-	++	++	++	++	++	++
Comparability to other locations	++	++	++	++	++	++	++	++	++	+	+	+
Suitability for road surface classification	+	+(H) ++(E)	++	+	+(H) ++(E)	++	+	+(H) ++(E)	++	+	+(H) ++(E)	++

++ very well adapted ; + adapted ; - poorly adapted ; -- not adapted

### 2.1.4 Contribution of the powertrain noise: the ISO 362 standards

The ISO 362 standards specify an engineering method for measuring the noise emitted by road vehicles of specific categories. The specifications are intended to reproduce the noise level generated by the principal noise sources during normal driving in urban traffic. These standards are:

- EN ISO 362-1: 2007 (ISO, 2007). This part of ISO 362 concerns the road vehicles of categories M (power-driven vehicles having at least four wheels and used for the carriage of passengers) and N (power-driven vehicles having at least four wheels and used for the carriage of goods)
- EN ISO 362-2: 2009 (ISO, 2009). This part of ISO 362 concerns the road vehicles of category L3, L4 and L5 (motor vehicles having fewer than four wheels). Vehicles in this category are not in the scope of the project FOREVER.
- ISO CD 362-3: 2012 (ISO, 2012-2). This part of ISO 362 describes an indoor testing of M and N categories.

The vehicles of category L1 and L2 (mopeds) are covered by the ISO 9645 standard, not reported here.

#### 2.1.4.1 The EN ISO 362-1 standard

The EN ISO 362-1 standard describes an engineering method for measuring the noise emitted by road vehicles of categories M and N under typical urban traffic conditions. In order to take into account all the various situations encountered in urban driving conditions, a lot of parameters are introduced in the procedure. It requires a particular attention on the measurement characteristics:

- The measurement has to be carried out in open field conditions, without reflective obstacles in the vicinity of the test area (< 50 m). The test area has to be at least 20 m wide and 20 m long and covered with a reflective pavement according to the ISO 10844 standard<sup>7</sup>.
- Microphones are classically located in the standard position (1.2 m above the ground and 7.5 m from the centreline). Their electroacoustical characteristics have to comply with the IEC 61672-1 standard<sup>8</sup>.
- The signal recording is activated when the vehicle runs between two measurement lines located 10 m before and after the microphone position (cf. Figure 2).
- Measurements have to be performed under controlled weather conditions.

Figure 2 illustrates the general disposition of the test site.

<sup>7</sup> ISO 10844 :2011 – Acoustics – Specification of test tracks for measuring noise emitted by road vehicles and their tyres.

<sup>8</sup> IEC 61672-1 :2002 Electroacoustics – Sound level meters. Part 1 : specifications

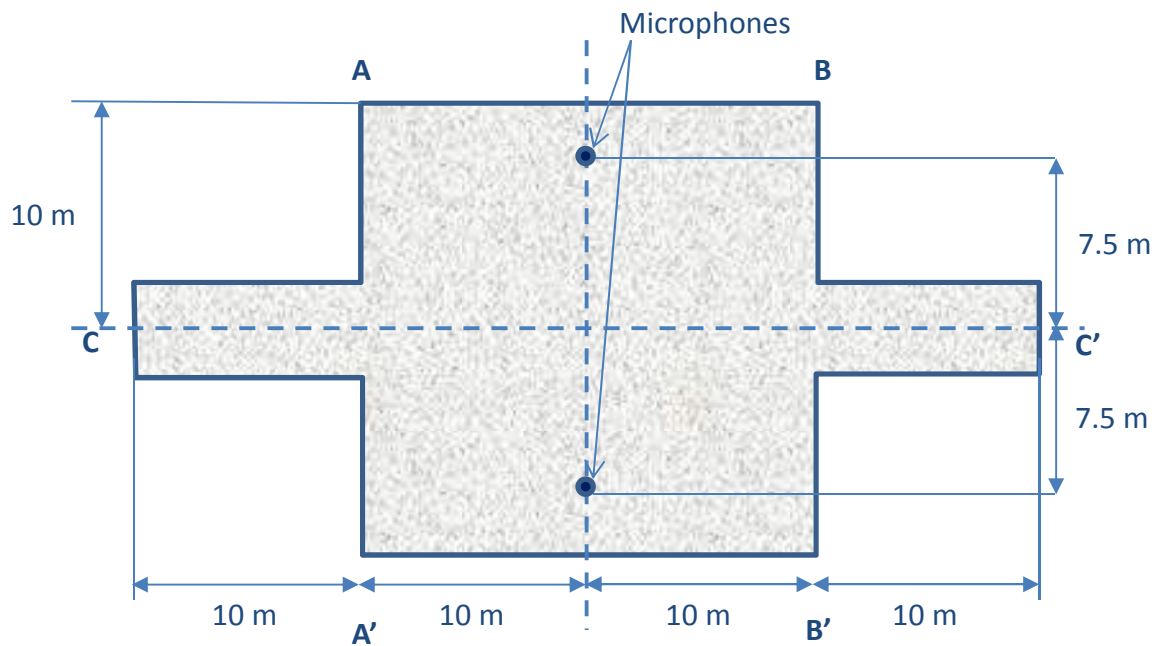


Figure 2: EN-ISO 362-1: test site requirements. The shaded test area must be fitted with a surface complying with ISO 10844. These test site requirements are also valid for EN-ISO 362-2 measurements.

The noise measurements to be carried out and the operating conditions depend on the vehicle category. The key point concerns acceleration tests performed over the 20 m test area and the related operating method. Its main features are summed up below.

**For vehicles of categories M1, N1 and M2 with maximum authorized mass < 3500 kg:**

The two key parameters are the power-to-mass ratio index PMR and a wide-open-throttle reference acceleration defined as:

$$a_{wot,ref} = 1.59 \log(PMR) - 1.41 \quad \text{for } PMR \geq 25 \quad (5)$$

$$a_{wot,ref} = 0.63 \log(PMR) - 0.09 \quad \text{for } PMR < 25 \quad (6)$$

The noise is measured in two operating conditions:

- *an acceleration test*: pre-tests are required to determine the operating conditions appropriate to the vehicle. Typically, driving conditions are determined to allow the vehicle to fulfil both an acceleration target given by  $a_{wot,ref}$  and a target speed 50 km/h when some specific point on the vehicle is facing the microphone. The A-weighted maximum noise pressure level is recorded.
- *a constant speed test* at 50 km/h. The A-weighted maximum noise pressure level is recorded.

Finally, a weighted mean of the noise levels with acceleration and at steady speed provides an estimate of the urban noise level  $L_{urban}$ , reproducing partial throttle acceleration conditions.

### For vehicles of categories N2, N3, M3 and M2 with maximum authorized mass > 3500 kg:

The *wide-open-throttle test* is the only test for these heavy vehicle categories. The vehicle runs on the 20 m test area with full acceleration and the target speed is 35 km/h. The engine speed must be included within a predefined interval at the end of the test area. The A-weighted maximum noise pressure level directly provides the estimate of the urban noise level  $L_{urban}$ .

#### 2.1.4.2 The EN ISO 362-2 standard

This part of ISO 362 describes an engineering method for measuring the noise emitted by road vehicles of categories L3, L4 and L5 under typical urban traffic conditions. These vehicle categories are reported here for completeness although outside the scope of the FOREVER project. In the same way as specified in the EN ISO 362-1 procedure, the aim is to reproduce the noise generated in normal urban driving conditions (typically on roads with speed limits of 50 and 70 km/h).

The requirements of this procedure are similar to those described above, with two key parameters: a wide-open-throttle reference acceleration ( $a_{wot,ref}$ ) and the power-to-mass ratio (PMR) index.

For L3 vehicles<sup>9</sup> with  $PMR > 25$ :

$$a_{wot,ref} = 2.47 \log(PMR) - 2.52 \quad \text{for } 25 < PMR \leq 50 \quad (7)$$

$$a_{wot,ref} = 3.33 \log(PMR) - 4.16 \quad \text{for } PMR > 50 \quad (8)$$

The maximum A-weighted noise pressure level is measured in acceleration conditions akin to the above reference acceleration, respectively at constant speed, for a test speed in front of the microphone position of 40 km/h (for  $PMR \leq 50$ ) or 50 km/h (for  $PMR > 50$ ). The final noise result  $L_{urban}$  is a weighted combination of the respective levels reported under acceleration and at constant speed, reproducing partial throttle acceleration conditions.

For vehicle of category L3 with  $PMR \leq 25$ , the only operating condition is a wide-open-throttle acceleration test.

Note that the EN ISO 362-2 standard gives the possibility to perform indoor test operation using a dynamometer test bench simulating the road operation of the vehicle. This facility shall be installed in a hemi-anechoic room. The indoor method eliminates restrictions due to ambient outdoor conditions.

#### 2.1.4.3 The EN ISO 362-3 standard

This standard specifies an engineering method for measuring the noise emitted by road vehicles of categories M and N by using a semi-anechoic chamber. The specifications are intended to achieve a correlation between testing the exterior noise of road vehicles in indoor conditions and the outdoor testing as described in the EN ISO 362-1 standard.

The general requirements and specifications are similar to those described in the EN 362-1 standard. The main difference concerns the test room requirements. The EN ISO 362-1

<sup>9</sup> two-wheeled vehicles with engine capacity greater than 50 cm<sup>3</sup> or max. speed greater than 50 km/h



procedure imposes that tests shall be performed in free-field conditions. To reproduce this acoustic criterion indoors, the room-design must be able to provide a semi-anechoic space with the same effective propagation characteristics as an open space over a reflecting surface. An example of test room is shown in Figure 3.

The measurement requires a set of microphones placed along a line at the distance of 7.5 m from the longitudinal centreline and extending 10 m on both sides of the vehicle. The standard outdoor pass-by noise characteristics are synthesized, either by combining indoor noise measures with outdoor rolling noise measures (variant A) or from indoor measurement only (variant B).

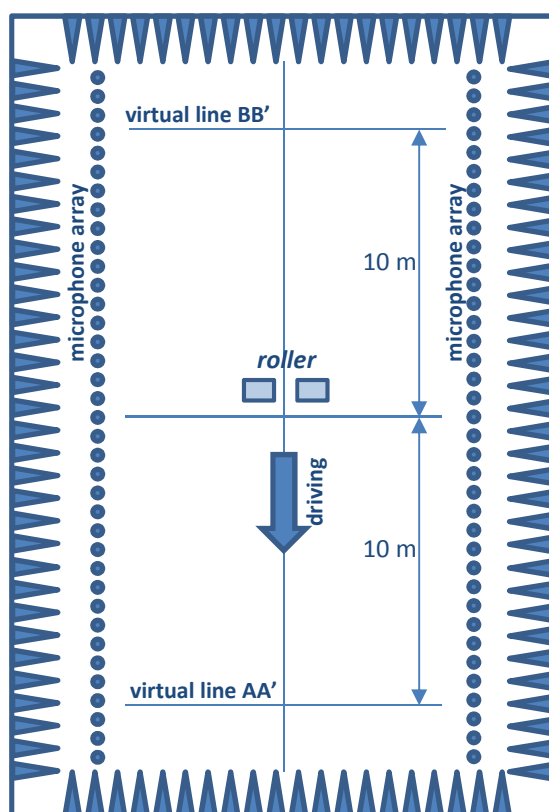


Figure 3: Example of a test room for indoor pass-by synthesis.

#### 2.1.4.4 Comments on EVs/HEVs and the ISO 362-1/2/3

The ISO 362/1/2/3 is used for type approval. The vehicle operating conditions accepted in the standard intend to reproduce the contribution of the principal noise sources in normal urban driving conditions, rendering noisy realistic situations. As an example for the selection of the standard specifications, inquiries conducted on dwellers in Germany are cited, which indicate that the expressed noise annoyance and disturbance primarily concern urban main streets where the allowed speed is 50 km/h and during vehicle acceleration transients. Statistics pointing out that these are the most frequent traffic conditions on the main roads are given as well.

In the case of a future traffic composed of a significant part of EVs, it could be interesting to study whether the driving conditions and speeds associated with high annoyance would differ

from the case with conventional engine vehicles, and thus check the accordance of the standard procedure with the population feeling in that case. In the conclusions of the European project CityHush, P. Stenlund (2011-1) recommended to perform the wide-open-throttle test of ISO 362 at a lower start speed for the electric cars equipped with a weak engine ( $PMR < 40$ ), and proposed 30 km/h as an appropriate speed.

Finally, the testing of quiet vehicles requires a low background noise level in order to provide meaningful vehicle noise measures, implying that favourable environmental conditions may be difficult to fulfil on common outdoor test sites. The ISO 362-3 can provide a useful solution to this perspective.

## 2.2 Noise source analysis with a microphone array

A microphone array is an acoustic measurement device composed of a set of omnidirectional microphones. By an appropriate combination of the microphone signals, it comes down to a directive measurement device, able to separate signals coming from distinct space areas, for instance to separate signals from a source area on a vehicle from its neighbouring sources. The microphone distribution in space is decisive for the array performance. The array processing often used with microphone arrays for the analysis of vehicle noise sources at pass-by is the delay-and-sum beamforming.

### Principle of beamforming

Let an array be composed of  $N$  microphones of respective coordinates  $(x_n, y_n, z_n)$  with  $n = 1 \dots N$ . Let a monopole source be located at point  $S$  of coordinates  $(x_S, y_S, z_S)$  (see Figure 4). In nearfield conditions where the wave fronts radiated by the source are spherical, the signal received on sensor  $n$  is:

$$p_n(t) = \frac{1}{4\pi r_{Sn}} s\left(t - \frac{r_{Sn}}{c}\right) \quad (9)$$

where  $r_{Sn}$  is the distance from the source  $S$  to sensor  $n$ , and  $c$  is the sound velocity.

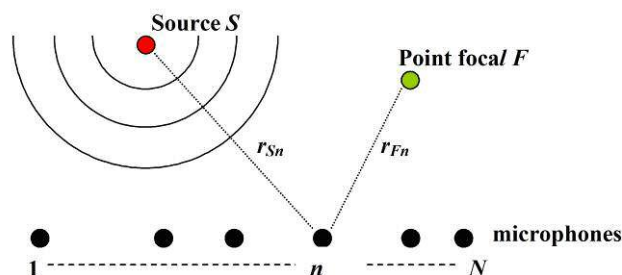


Figure 4: Diagram of the microphone array, the source  $S$  and the focal point  $F$

Delay-and-sum beamforming consists in compensating the propagation delays on the respective microphone signals in order to align the signals in phase, assuming the source to be at a given point  $F$ , and then averaging the signals. The output signal of the beamformed array focused on focal point  $F$ , in the maximum likelihood sense, is:

$$p(F,t) = \frac{\sum_{n=1}^N \frac{w_n}{r_{Fn}} p_n \left( t + \frac{r_{Fn}}{c} \right)}{\sum_{n=0}^N \frac{1}{r_{Fn}}} \quad (10)$$

where  $r_{Fn}$  is the distance between the focal point  $F$  and the sensor  $n$ . The  $w_n$ , such that  $\sum_{n=1}^N w_n = 1$ , are the shading coefficients. The array favours signals coming from a source located at the focal point, while signals from sources located elsewhere are attenuated. This attenuation depends on:

- the array geometry (space distribution of sensors, size of the array)
- the source frequency
- the relative positions of the focal point and the source
- the coefficients  $w_n$

More details can be found in (Johnson, 1993). The distance between neighbouring microphones must be small enough to fulfil the Shannon condition for correct wave sampling at all frequencies. In order to keep constant spatial performance of the array over the useful frequency range, the shading coefficients can be specified as frequency dependent.

For separating several sources distributed in a plane, a 2-dimensional array has to be used. By scanning the source domain with the focal point, the actual location of the sources can be detected and the source strengths can be estimated. This method requires a multi-channel data acquisition system for recording the signals.

A limitation of the method at low frequency relates to the spatial resolution, which can be insufficient to separate close sources on a vehicle.

### Application to moving sources and vehicles

In the case of a moving source, microphone signals are affected by variable frequency shifts through the Doppler effect and by unstationary conditions. A dedopplerization procedure allows the user to compensate for the frequency shifts and to track the moving source as well, thus increasing the exposure duration and the accuracy of the source analysis. This step requires information on the position and speed of the vehicle, taken simultaneously to the acoustical recordings.

At the end of the source scanning process at vehicle pass-by, a noise map of the side noise emission is built, per frequency band or in global noise levels (see Figure 5). It can be improved by the use of deconvolution methods in order to cancel blurring introduced by the array pattern. With further analysis, noise emission models can be determined for the main noise source areas.

Compared with common measurement methods involving a single microphone, microphone array methods have the following properties:

#### Advantages:

- Identification of the spatially-distinct noise sources on the vehicle
- Provides a source-oriented model of the vehicle noise emission

- Low sensitivity to background noise
- Production of noise emission maps of the vehicle at pass-by

Disadvantages:

- poor spatial resolution at low frequencies
- inaccurate estimation of the noise source location and strength if the physical source differs strongly from a compact source / monopole (in particular forward or backward highly directive source)
- higher equipment cost, processing and computational load

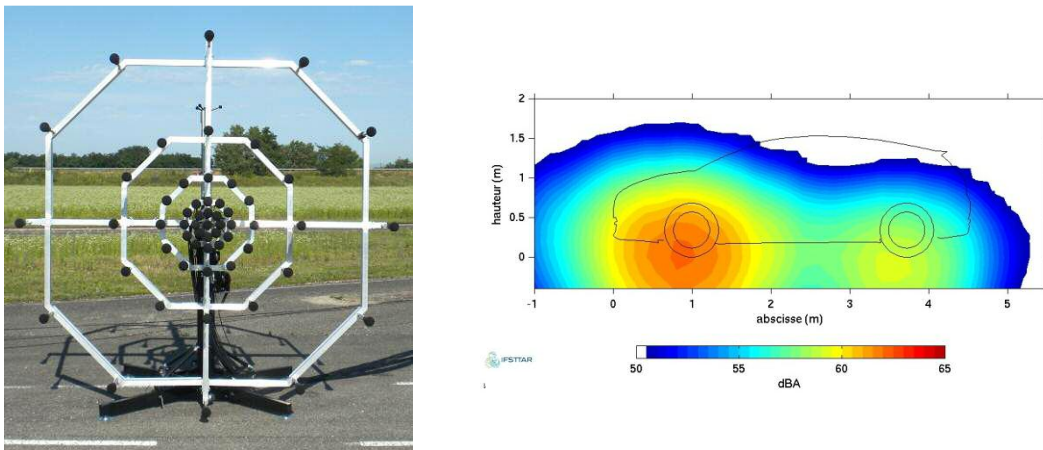


Figure 5: Exemple of a two-dimensional microphone array (*left*) and global noise map of a hybrid car (*right*). [source IFSTTAR]

### 2.3 Measurement of the minimum noise emission

Standards have been recently published, specifically devoted to low noise vehicles. They concern the measurement of a minimum noise emission, with the background of preserving the safety of pedestrians through the audibility of the vehicle.

Considering that electric and hybrid vehicles may be too silent to be detected by pedestrians when stopped, moving at low speed or commencing motion, the standard SAE J2889-1 has been published in 2012 to determine the minimum noise emission of vehicles (SAE, 2012). A new version is currently prepared under reference ISO/CD 16254 (ISO, 2013-2). Both are technically similar. One part of these standards concerns the evaluation of an external sound generation system, if available. The present subsection reports the measurement specification of the minimum vehicle noise emission, apart from those specific to the sound system.

For outdoor measurement, the characteristics of the test site are similar to those of the pass-by tests previously described, with a 20 m long test area, free of reflecting objects. For the full vehicle testing, the microphone is located at 2 metres from the track centre and 1.2 metre above the ground level. Indoor measurement is also allowed. The vehicle operating conditions include:

- vehicle stopped in front of the microphone: the minimum A-weighted sound pressure level  $L_{stop}$  is reported.
- slow speed cruise at 10 km/h: the maximum A-weighted sound pressure level  $L_{crs}$  during pass-by is reported.

One-third-octave results shall be reported at the time of each A-weighted sound pressure level specified above. A measure with the vehicle commencing motion is intended for the evaluation of the sound system.

A specificity of these standards concern how the background noise is taken into account and corrections are proposed. The background noise reference is the minimum A-weighted sound pressure level recorded in a 10-second sample, as well as the corresponding one-third-octave frequency spectrum. Since background noise level is crucial and may become problematic in case of low noise source measurement in outdoor environment, the use of correction terms to be applied to the measured noise levels is allowed from a 10 dB down to a 3 dB difference between the overall test value and the background noise level, as illustrated in Table 2 for background noise levels larger than 25 dB(A).

Table 2: Correction to be applied to the test results according to SAE J2889-1 and ISO/CD 16254 for a background noise level larger than 25 dB(A) and peak-to peak fluctuation smaller than 2 dB(A)

Test result minus background noise level	Correction
> 10 dB	0 dB
8 dB to 10 dB	0.5 dB
6 dB to 8 dB	1.0 dB
4.5 dB to 6 dB	1.5 dB
3 dB to 4.5 dB	2.5 dB
< 3 dB	X

These standards are intended to be used in relation with regulations specifying a minimum noise level for low noise vehicles.

## **2.4 Description of individual vehicles in the noise assessment methods**

Various road traffic noise prediction models have been developed in different countries for the noise assessment of road infrastructures (Garg, 2014). These models generally include both a vehicle noise emission model and a propagation model. This subsection reviews the sole source description used for road traffic noise in these prediction models, representing the sound emitted by an average individual vehicle of the traffic. These vehicle noise emission models have different features and are adapted to specific road network and road surfaces, traffic flow and vehicle types. The sound representation of the vehicles in the following models is briefly described:

- the American model developed by the Federal Highway Administration (FHWA)
- the Japanese ASJ-RTN model
- the Nord2000 model developed by the Nordic European countries
- the Harmonoise/Imagine model, developed by several western European countries in the frame of a European research project
- the Swiss model OFPE
- the German model RLS 90
- the French model NMPB08
- the CNOSSOS-EU model

At the end of the subsection, the main features of these vehicle noise emission models are compared in a summary table.

In the further work of the project FOREVER, the CNOSSOS-EU vehicle model is deepened in relation with electric and hybrid vehicles.

#### **2.4.1 Federal Highway Administration Traffic Noise Model (FHWA-TNM)**

The FHWA-TNM (FHWA-TNM, 1998) is the highway traffic noise prediction model available in the United States. As sources of noise, it provides the maximum A-weighted sound pressure levels and one-third octave-band spectra of the noise radiated by a vehicle at a 15 m distance from the road. These input data result from measurement campaigns carried out to determine vehicle noise emission, considering different vehicle types, road pavements, vehicle speeds and throttle positions. These levels were analysed to find out a general equation governing the radiated sound levels, generally referred to as REMEL (Reference Energy Mean Emission Levels). The FHWA-TNM model considers five categories of vehicles:

- automobile (gross vehicle weight < 4.5 t)
- medium trucks
- heavy trucks
- buses
- motorcycles

The energy radiated is split into two separate noise sources, respectively located at a height of 0 m and 1.5 m, except for heavy trucks whose higher source is at 3.66 m. The ratio of sound energy distributed to each sub-source is variable. Four road pavements and two throttle positions (cruising or full-throttle) are considered. To compute the sound pressure level in dB(A), FHWA-TNM uses three constant coefficients (A, B, C). The A-weighted SPL at 15 m is given by:

$$L(v) = 10 \log \left( (0.6214 v)^{A/10} 10^{B/10} + 10^{C/10} \right) \quad [\text{dB(A)}] \quad (11)$$

where  $v$  is the vehicle speed in km/h. Fourteen additional coefficients need to be considered to convert the A-weighted noise levels to third octave band spectra. All the seventeen coefficients depend on the vehicle type, road pavement and vehicle throttle position.

This model does not estimate engine noise and tyre noise separately but gives the total sound pressure level radiated by a conventional engine vehicle at a 15m distance from the road.

A proposal of REMEL input data for electric vehicles was recently made; it is presented in the literature review in section 0.

### 2.4.2 ASJ-RTN model

The Japanese traffic noise model considers each vehicle constituting the traffic as a single point source (Yamamoto, 2010). No separation between engine and tyre/road noise is considered. Depending on the expected precision of the model, two categories of vehicles (light and heavy vehicles) or four (passenger cars, small-sized vehicles, medium sized vehicles, large sized vehicles) – and optionally a motorcycle category – are considered in two running conditions (steady and non-steady speed). Two different road pavements (dense and porous asphalt), road gradients and source directivity are taken into account. The A-weighted sound power level emitted by a vehicle is expressed as:

$$L_{WA}(v) = a + b \log(v) + \Delta L_{surf} + \Delta L_{grad} + \Delta L_{dir} \quad [\text{dB(A)}] \quad (12)$$

where:

- $v$  is the vehicle speed in km/h
- $a$  and  $b$  are regression coefficients
- $\Delta L_{surf}$  [dB(A)] is the correction for porous asphalt (ref. to dense asphalt)
- $\Delta L_{grad}$  [dB(A)] is the correction for road gradient
- $\Delta LA_{dir}$  [dB(A)] is the correction for sound radiation directivity.

Octave and third octave band levels can also be estimated using equation:

$$L_{WA}(v, f) = L_{WA}(v) + \Delta L_{WA}(f) \quad [\text{dB(A)}] \quad (13)$$

The values for the regression and correction coefficients can be found in (Yamamoto, 2010).

### 2.4.3 Nord2000 model and Harmonoise/Imagine models

These models use different approaches for sound propagation but the source modelling is common (Jonasson, 2006), (Jonasson, 2004). Four vehicle categories<sup>10</sup> are considered in Imagine: light vehicles, medium heavy vehicles, heavy vehicles, and two-wheelers. The separate equations used to estimate the sound power levels govern engine and tyre/road noise respectively. For both components, correction factors can be applied to simulate non-standard road surfaces, road gradients, vehicle transient running conditions and other particular conditions. The general equation for the sound power level due to propulsion noise is:

$$L_{wp}(v, f) = A_p(f) + B_p(f) \left( \frac{v - v_{ref}}{v_{ref}} \right) + \Delta L_{wp,road}(v, f) + \Delta L_{wp,other}(v, f) \quad (14)$$

where :

- $v$  is the speed [km/h]
- $v_{ref} v_{ref} = 70$  km/h
- $f$  is the frequency in Hz

<sup>10</sup> Three categories for Nord2000: light, medium and heavy vehicles.

- $A_p(f)$  and  $B_p(f)$  are coefficients obtained from tables provided in (Jonasson, 2004) for Harmonoise model and (Jonasson, 2006) for Nord2000 model.
- $\Delta L_{wp,road}(v, f)$   $\Delta L_{wp,road}(v, f)$  is the correction factor accounting for the effect of the road surface on the propagation of propulsion noise.
- $\Delta L_{wp,other}(v, f)$   $\Delta L_{wp,other}(v, f)$  is the correction factor accounting for vehicle acceleration, road gradient, percentage of diesel vehicles and proportion of delivery vans (for light vehicles only)

The general equation of the sound power level due to the tyre/road interaction noise is:

$$L_{wr}(v, f) = A_r(f) + B_r(f) \log(v/v_{ref}) + \Delta L_{wr,road}(v, f) + \Delta L_{wr,region}(v, f) \quad (15)$$

where:

- $A_r(f)$   $A_r(f)$  and  $B_r(f)$   $B_r(f)$  are coefficients provided in (Jonasson, 2004) for Harmonoise model and (Jonasson, 2006) for Nord2000 model.
- $\Delta L_{wr,road}(v, f)$   $\Delta L_{wr,road}(v, f)$  and  $\Delta L_{wr,region}(v, f)$   $\Delta L_{wr,region}(v, f)$  are correction factors accounting for various environmental and traffic parameters such as air temperature, road humidity, road pavement, number of axles per vehicle, number of tyres per axle, tyre width and proportion of delivery vans.

The propulsion and tyre/road noise sound power levels are assigned to two equivalent point sources. One is located at 0.01 m above the road and the second one at 0.3 m (light vehicles) or 0.75 m (heavy vehicles). The lower source carries 80% of the rolling noise and 20% of the propulsion noise. The upper source carries 80% of the propulsion noise and 20% of the rolling noise, for all vehicle categories.

#### 2.4.4 The Swiss OFEV models

##### The StL-86+ Model (OFEV, 1987)(OFEFP, 1995)

The StL-86, dedicated to the prediction of road traffic noise and developed by the Swiss Federal Office for the Environment (FOEN), is based on data collected during the 80's. In 1995, the FOEN updated the method which was re-called StL-86+.

The general equation giving the A-weighted equivalent level at a distance of 1 m is:

$$L_{eq} = A + 10 \log \left[ \left( 1 + \left( \frac{v}{50} \right)^3 \right) \cdot \left( 1 + B \cdot \eta \cdot \left( 1 - \frac{v}{150} \right) \right) \right] + 10 \log(M) \quad (16)$$

where:

- $A$  and  $B$  are empirical constants ( $A = 43$  ;  $B = 20$ )
- $v$  is the speed
- $\eta$  is the proportion of heavy trucks present in the total traffic
- $M$  is the flow rate (vehicle/h)

A correction factor  $K$  is proposed in order to take into account the increase of emitted noise for slopes larger than 3%:

$$K = (s - 3) \cdot 0.5 \quad \text{for slopes } s > 3\% \quad (17)$$



## The SonRoad Model (OFEV, 2004)

This model, developed by EMPA and published in 2004, is derived from ISO 9613-2 specifications. In this model, the vehicle is represented by a point source at 0.45 m above the ground. The engine and tyre/road components are calculated separately as a function of speed, slope, road surface and traffic flow characteristics. Two categories of vehicles are considered (light vehicles and trucks). The global  $L_{Amax}$  levels (estimated at the distance of 7.5 m from the road centreline and at 1.2 m high) are given by the following expression:

$$L_{Amax}(v) = L_p(v) \oplus L_r(v) + \Delta_s + \Delta_r \quad (18)$$

where:

- $L_p$  corresponds to the propulsion noise component :

$$L_p(v) = A_p + B_p \log \left[ 1 + \left( \frac{v}{v_0} \right)^{3.5} \right] \quad (19)$$

- $L_r$  corresponds to the tyre/road noise component :

$$L_r(v) = A_r + B_r \log(v) \quad (20)$$

- $A_p$ ,  $B_p$ ,  $A_r$  and  $B_r$  are coefficients defined for each vehicle category
- $\Delta_s$  is a correction factor taking into account the noise increase due to slopes:
- $\Delta_s = 0,8g$  where  $g$  is the percentage of slope
- $\Delta_r$  is a correction factor taking into account the type of road surface.

The noise spectrum is provided in one-third octave bands.

### 2.4.5 The German model RLS 90

The RLS 90 model (Richtlinie für den Lärmschutz an Straßen – Guidelines for Noise Protection on Roads) is the German prediction method for new roads and for existing roads with substantial changes (i.e. new lanes) (RLS 90, 1990) (Hamet, 1996).

This model provides A-weighted equivalent noise pressure levels on a period of 1 hour, for a traffic flow including a specified part of heavy vehicles, at a distance of 25 m and a height of 4 m, in the reference conditions:

- horizontal, infinitely long road
- road surface reference which is non-grooved poured asphalt concrete

The equivalent noise level for a light vehicle at the steady speed  $v_{Pkw}$  is expressed by:

$$L_{Pkw}(v_{Pkw}) = 27.7 + 10 \log[1 + (0.02v_{Pkw})] \quad (30 \leq v_{Pkw} \leq 130 \text{ km/h}) \quad (21)$$

whereas for a heavy truck (> 2.8t) at the steady speed  $v_{Lkw}$  the equivalent level is given by:

$$L_{Lkw}(v_{Lkw}) = 23.1 + 10 \log[v_{Lkw}] \quad (30 \leq v_{Lkw} \leq 80 \text{ km/h}) \quad (22)$$

Correction factors are provided for road surface types different from the reference surface and for roads with gradients.

### 2.4.6 The French model NMPB08

The French traffic noise model, called NMPB 2008 (NMPB08, 2009), provides two types of acoustic quantities for the vehicle noise sources: the maximum sound pressure levels ( $L_{Amax}$ ) at a distance of 7.5 m from the road and a height of 1.2 m and the sound power levels per metre of road and per vehicle ( $L_{w/m/veh}$ ).

For each indicator, two sources (engine and tyre/road noise components) are considered separately, but the sound levels are assigned to a single equivalent source at a height of 0.05 m. Two categories of vehicles are distinguished: light vehicles (< 3.5 t) and heavy vehicles (>3.5 t). Three driving conditions are considered (steady speed, acceleration and deceleration). Road declivity is also taken into account.

For one vehicle, the general relation is:

$$L_{W/m/veh} = L_{r_{W/m}} \oplus L_{p_{W/m}} = 10 \log [10^{0.1L_{r_{W/m}}} + 10^{0.1L_{p_{W/m}}}] \quad (23)$$

where

- $L_{r_{W/m}}$  is the tyre/road noise component
- $L_{p_{W/m}}$  is the power unit noise component

Basically,  $L_{W/m/veh}$  values in dB(A) can be estimated from  $L_{Amax}$  levels using the following relation, assuming the source to be an omnidirectional point source:

$$L_{W/m/veh} \cong L_{Amax} - 10 \log V - 4.4 \quad (24)$$

where  $V$  is the speed expressed in km/h and

$$L_{Amax} = L_{Armax} \oplus L_{Aprmax} \quad (25)$$

The rolling noise component  $L_{r_{W/m}}$  (resp.  $L_{Armax}$ ) depends on vehicle speed and on the road surface and was determined on the basis of pass-by measurements performed according to the SPB or the CPB procedures over a large sample of road surfaces and addresses the different pavement types and age. The road pavement influence is addressed by grouping the pavement types in three categories (R1, R2, and R3), each with its  $L_{r_{W/m}}$  law for each vehicle category.

The power unit noise  $L_{p_{W/m}}$  (resp.  $L_{Aprmax}$ ) component is given as a function of traffic speed and acceleration, and of road declivity. This was determined on the basis of two types of information: the vehicle's power unit noise emission in function of speed, gear ratio and acceleration (power unit noise emission laws) and statistics on the way the vehicles are driven in traffic (driving behaviour).

Distributions of the emitted noise in third-octave bands are provided in the frequency range [100 Hz - 5000 Hz], distinguishing two road types: porous asphalt on one hand, all other surfaces on the hand.

### 2.4.7 The CNOSSOS-EU model

The Common NOise aSSessment methOdS (CNOSSOS-EU) are elaborated with the main objective to build a set of consistent tools providing comparable results from the strategic noise mapping carried out by the EU member states to fulfil their obligation under the European Directive on the Assessment and Management of Environmental Noise (2002/49/EC) (CNOSSOS-EU, 2011).

Concerning road traffic noise sources, the CNOSSOS-EU model is based on a combination of separate categories forming the traffic:

- Category 1 : Light motor vehicles
- Category 2 : Medium heavy vehicles
- Category 3 : Heavy vehicles
- Category 4 : Powered two-wheelers

In each category, the individual vehicle is represented by one single point source placed 0.05m over the road surface. The noise contribution of a vehicle is described by the sound power emitted in dB in semi-free field conditions. The emission model consists of a set of mathematical equations representing the two main sources (tyre/road interaction noise and driveline noise) as a function of vehicle speed  $v$  ( $20 \text{ km/h} \leq v \leq 130 \text{ km/h}$ ), and whose coefficients are given in octave bands (from 63 Hz to 8000 Hz) for each category. However, the method is indicated as being valid from 125 Hz to 4000 Hz.

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

$$L_{WR} = A_R + B_R \log\left(\frac{v}{v_{ref}}\right) + \Delta L_{WR}(v) \quad (26)$$

where

- $A_R$  and  $B_R$  are coefficients expressed in octave bands (from 63 Hz to 8000 Hz) for each vehicle category, and for the reference speed  $v_{ref} = 70 \text{ km/h}$ .
- $\Delta L_{WR}(v)$  is a sum of correction factors taking into account respectively the road surface type, the proportion of vehicles with studded tyres, the effect of acceleration near traffic lights or roundabout, the effect of temperature  $\tau$ :

$$\Delta L_{WR}(v) = \Delta L_{WR,road}(v) + \Delta L_{studded}(v) + \Delta L_{WR,acc} + \Delta L_{W,temp}(\tau) \quad (27)$$

The propulsion noise is defined as a linear function of the speed  $v$ . It includes the contributions from engine, exhaust, gears, air intake, etc. The sound power level  $L_{WP}$  is formulated by:

$$L_{WP}(v) = A_P + B_P \left(\frac{v - v_{ref}}{v_{ref}}\right) + \Delta L_{WP}(v) \quad (28)$$

where

- $A_P$  and  $B_P$  are coefficients expressed in octave bands (from 63 Hz to 8000 Hz) for each vehicle category, and for the reference speed  $v_{ref} = 70 \text{ km/h}$ .

- $\Delta L_{WP,road}$  is a sum of correction coefficients for conditions deviating from the reference conditions, accounting respectively for the road surface type, the effect of acceleration near traffic lights or roundabouts, and the effect of road gradients:

$$\Delta L_{WP}(v) = \Delta L_{WP,road}(v) + \Delta L_{WP,acc} + \Delta L_{WP,grad}(v) \quad (29)$$

The reference conditions are:

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

Figure 6 and Figure 7 illustrate respectively the rolling sound power levels and the propulsion sound power levels for the different categories of vehicles in reference conditions.

It is worthwhile noticing that CNOSSOS-EU foresees a fifth vehicle category as an open class for new vehicles to be developed in the future, which would be sufficiently different from conventional engine vehicles to require a new category. Electric or hybrid vehicles are explicitly cited as an example.

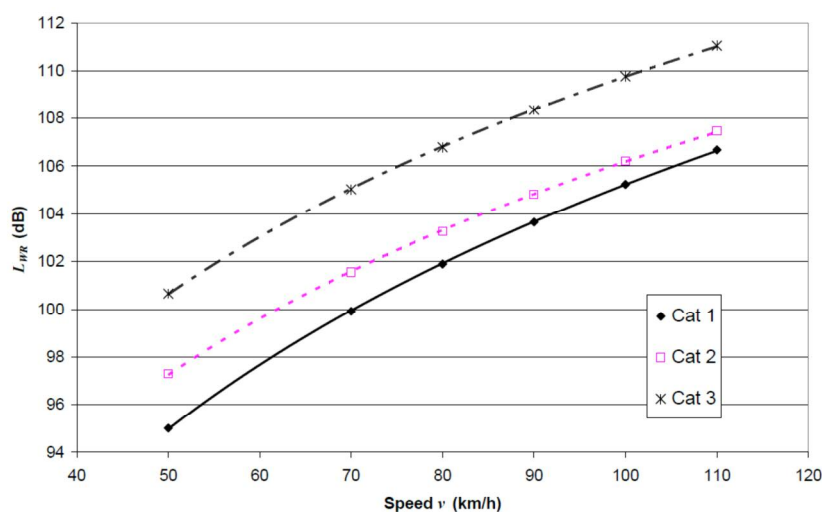


Figure 6: Rolling sound power levels in dB for the first categories of vehicles in reference conditions. (The figure is taken from (CNOSSOS-EU, 2012))

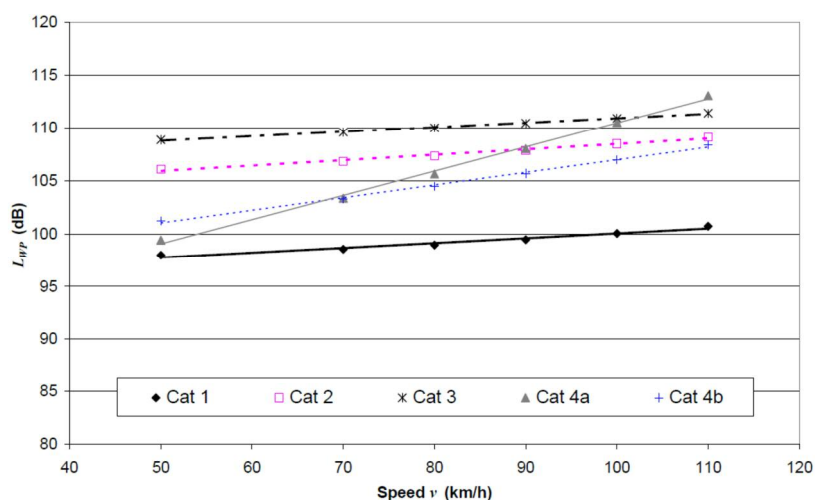


Figure 7: Propulsion sound power levels in dB for all categories of vehicles in reference conditions. (The figure is taken from (CNOSSOS-EU, 2012))

#### 2.4.8 Summary of the characteristics of the vehicle noise emission models

Table 3 summarizes the main features of the individual vehicle noise emission models analysed in this report.

Most of the recent prediction models which have been developed in Europe use a vehicle noise description split into a rolling noise component and a powertrain component, and also provide frequency information. The vertical description of the vehicles involves either one or two point sources with various source heights.

Since CNOSSOS-EU has a transnational scope and is intended to harmonize the production of strategic noise maps in Europe, this model has been selected for consideration in FOREVER in regard to EVs and HEVs. In addition, its structure offers in advance the opportunity to include a new vehicle category if the need arises for EVs or HEVs.

Table 3: Comparison of the main features of the road vehicle noise prediction models.

Model	FHWA-TNM	ASJ-RTN	Nord 2000	Harmonoise /Imagine	Slt-86+	SonRoad	RLS-90	NMPB 2008	CNOSSOS -EU
<i>Region</i>	<i>North America</i>	<i>Japan</i>	<i>North Europe</i>	<i>West Europe</i>	<i>Switzerland</i>	<i>Switzerland</i>	<i>Germany</i>	<i>France</i>	<i>Europe</i>
<b>Estimated sound level</b>	$L_{Amax}$ at 15m	$L_w$	$L_w$	$L_w$	$L_{Aeq}$	$L_{Amax}$ , $L_w$	$L_{Aeq,1H}$ at 25m	$L_{Amax}$ , $L_w/m/veh$	$L_w$
<b>Engine/tyre separation</b>	<i>no</i>	<i>no</i>	<i>yes</i>	<i>yes</i>	<i>no</i>	<i>yes</i>	<i>no</i>	<i>yes</i>	<i>yes</i>
<b>Number of equivalent sources</b>	2	1	2	2	1	1	1	1	1
<b>Source 1 height (m)</b>	0	NA	0.01	0.01	0.8	0.45	0.50	0.05	0.05
<b>Source 2 height (m)</b>	1.5 or 3.66 (HT)	NR	0.3 (LV) or 0.75 (HT)	0.3 (LV) or 0.75 (HT)	NR	NR	NR	NR	NR
<b>Nb vehicle categories</b>	5	2 or 4 + MTC	3	4	2	2	2	2	4
<b>Nb road surfaces</b>	4	2	NA	7	3	13	4 or 5	15*	15
<b>Spectrum information</b>	1/3 octave	octave 1/3 octave	1/3 octave	1/3 octave	<i>no</i>	1/3 octave	<i>no</i>	1/3-octave	octave

\* These road surfaces are aggregated into 3 categories.

LV = light vehicles ; HT = heavy trucks ; MTC = motorcycles

NA not available (or not explicit) ; NR not relevant

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### 3 Review of exterior noise emission from electric and hybrid/electric vehicles

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) still account for a small part of the world's vehicle production. This proportion has been increasing significantly during the past few years and is expected to rise further over the next decade with a widening range of clean vehicles offered by automotive manufacturers, the development of charging infrastructure, together with stimulation by government policies and incentives in several countries. However, current knowledge is rather limited regarding the noise emission of these vehicles.

Many noise assessments available in existing literature on EVs and HEVs relate to perceptive studies, mainly for safety purposes concerning pedestrians and vulnerable road users like visually impaired people. Generally performed in non-standard measurement conditions, specifically designed for the needs of each study, they sometimes provide comparative evaluation of low-noise vehicles with traditional ICE vehicles in several driving conditions. Although they are not appropriate for inferring road traffic noise emission in connection with noise impact, a review of these noise assessment results is provided in the first part of this section for their valuable informative content.

A literature review of noise evaluations more relevant to the context of noise impact studies, implying non-standard or standard measurement conditions, is presented in a second subsection. Most of these studies were motivated by environmental issues and noise annoyance.

A summary of the main findings on EVs and HEVs noise emission, retrieved from the cited perceptive or impact studies, completes this literature review.

#### 3.1 *Non-standard noise emission data issued from perceptive studies*

The present section neither consists of an exhaustive literature review of auditory perception studies achieved on electric and hybrid electric vehicles, nor does it address the perceptive outcomes issued from the cited references. However, it focuses on the quantitative issues informing on vehicle noise emission provided in these references.

Light vehicles are chiefly concerned, but one study involving buses is also examined. A common feature of these studies relates to the driving and measuring conditions investigated, compatible with potentially tricky urban situations implicating pedestrians or bicyclists: low approach speed, moving off, and measurement at low distance from the driving lane. Specific manoeuvres like reverse driving and parking operations are not reported here, due to their marginal relevance for the project FOREVER. Studies involving measurements with microphones or sound level meters are retained.

A JASIC document reports a study dealing with the acceptability of warning systems on quiet vehicles (JASIC, 2009). It presents noise measurement performed on a test track in a remarkably quiet background environment, and compares noise emission from a hybrid electric passenger car driven in electric propulsion mode with two gasoline engine cars, from 0 (stationary) to 30 km/h. Although not explicitly specified in the document, it probably refers to constant speed pass-bys. Makes and models of vehicles and tyres are not given, nor the road surface type. Noise is measured on a microphone located 2 metres from the centre of the running lane, and the acoustic quantity considered is the equivalent noise sound level



$L_{Aeq}$ . The maximum noise level difference between the HEV in electric mode and both ICE cars occurs in stationary conditions and amounts to 20 dB(A). This difference reduces at higher speeds, reaches 7 dB(A) at 10 km/h and becomes small in the 20-30 km/h range. It may be suspected that rolling noise is already dominant in this upper speed range.

Wiener et al. (2007) investigated noise radiated by vehicles in street crossing environment, with the motivation of auditory detection ability by pedestrians. They studied the noise emission of a hybrid (Toyota Prius) and an ICE (Toyota Corolla) passenger car, chosen by the authors as being equivalent in size and power from the same car manufacturer. The cars were equipped with tyres from different brands. The experiment was conducted on a private street. The driving conditions investigated included: cruise-by and coast-by at 48 km/h, moving off with low acceleration so as to reach 10 km/h in 5 seconds (allows the Prius to run in electric mode), moving off in moderate acceleration so as to reach 29 km/h in 5 s (Prius with combustion engine working). A microphone was located 1.5 m from the vehicle (the reference on the vehicle is not specified) and 1.67 m high. Noise levels were recorded when the vehicles were at various distances upstream from the measurement point. For the accelerating vehicles, the article provides tables with sound pressure levels and octave spectrum. At coast-by and cruise-by, data is given only relatively to background noise. In any case, the actual acoustic quantities displayed are not explicitly indicated (maximum noise pressure levels and maximum noise spectra, or levels and spectra recorded at a specific vehicle position relatively to the microphone?). In their conclusions, the authors pointed out that the accelerating Corolla was 8 dB(A) noisier than the Prius with running ICE (both cars with moderate acceleration), and that the Corolla with moderate acceleration was 17 dB(A) noisier than the Prius in electric mode (low acceleration). Considering the measurement protocol, this 9 dB(A) difference for both drive-by conditions of the Prius in distinct powering modes may probably result from several factors at the same time: powertrain contribution, acceleration rate, noise levels taken at different instantaneous speeds, the two latest influencing also the rolling noise contribution. Finally, little difference was noticed between the vehicles at coast-by and cruise-by at 48 km/h, pointing out the low contribution of powertrain noise and the predominance of wind noise and rolling noise according to the authors.

Bräunl (2012) was turned towards warning sound system efficiency and acceptability. The author tried firstly to quantify the quietness of electric vehicles (without sound generator), considering two car categories: small cars and large cars. Therefore, he compared the noise emission of a Hyundai Getz in its petrol version to an electric version (REV Eco) on one hand, a petrol-driven BMW 535i to an electric converted Lotus Elise (REV Racer) on the other hand. Both electric vehicles were experimental cars developed within the REV project in Australia. No information on the measurement conditions and the acoustic quantities are provided, global sound levels were given at two distances 1.5 and 4.5 metres (no reference specified), from 10 to 70 km/h by 10 km/h steps. Even if not explicitly written, it concerned probably constant speed pass-bys. Some results were surprising. While the REV Getz was quieter than the petrol Getz by several dB(A) at all speeds (except 50 km/h) at 1.5 m distance, it proved louder at 4.5 m at 10 km/h and above 30 km/h. The petrol-driven BMW was definitely louder than the REV Racer, with major differences at low speed and low discrepancies above 50 km/h, but these cars can be hardly considered as really similar ones. The author underlined high noise level differences between the petrol and electric cars when accelerating from stationary, but figures usable for comparison were not provided. Thus, this study focusing on non-marketed vehicles has a limited scope for the project FOREVER.

The research conducted by Wall Emerson et al. (2011) was motivated by hazard and crossing decision by visually impaired people, and considered hybrid vehicles as potentially quiet vehicles. For assessing noise emission, four hybrid vehicles were investigated: Toyota

Prius, Honda Accord, Honda Civic, Ford Escape. ICE vehicles were recorded from the traffic, including heavy ones. The speed was almost constant for the test vehicles at pass-by, but generally slowing for the traffic vehicles. Average speed data was available. Noise measurement was performed with a sound level metre located 1 metre from the side of a roadway and at a height of 1.2 m. Global A-weighted maximum noise pressure levels were plotted for each vehicle (except Ford Escape) as a function of the pass-by speed, from about 10 to 45 km/h. The noise levels appeared rather scattered around the average trend for any hybrid vehicle, generally with a spread of 5 dB(A) but occasionally exceeding 10 dB(A), indicating probable measurement condition variations including the measurement distance which may have a main influence at such low distance. The dispersion for traffic vehicles was higher since it encountered many different vehicle models, brands and categories. The authors determined linear regression lines with the speed parameter  $v$ , regressions with  $\log v$  could probably give a better accordance with data. As for most studies, there was low sound level difference between the vehicle types at high speeds. Even if some ICE vehicles happened to be as quiet as the tested HEVs in the range 10-15 km/h, the HEVs were roughly 5 dB(A) quieter than the ICE vehicles on the average (occasionally up to 10 dB(A)).

The National Highway and Traffic Safety Administration (NHTSA) funded a research to examine the issue of quiet cars and safety of blind pedestrians. In the first phase of the programme, an evaluation of noise emission by hybrid vehicles was conducted in order to collect objective data in critical situations for pedestrians. The results have been reported in detail in (Garay-Vega, 2010) and main findings are available in (Hastings, 2011). Three hybrid vehicles were investigated, together with their closest ICE counterpart from the same brand: Honda Civic (hybrid / ICE), Toyota Prius (hybrid) and Toyota Matrix (ICE), Toyota Highlander (hybrid / ICE). All vehicles use a petrol engine, the Honda is a parallel hybrid, and the Toyotas are series-parallel hybrids. In all cases, the hybrid Honda could not be measured in all-electric mode and the engine was always running. Several operating conditions were tested:

- stationary at idle,
- constant speed pass-by at 10, 16, 32, 48 and 64 km/h,
- acceleration from stop 61 m upstream from microphone, up to 36 km/h
- deceleration from 32 km/h (upstream) to 16 km/h (right in front of microphone)

Measurement was performed on a test track with a microphone located at 3.66 m from the road centre line and a sound level meter at 15 m, both 1.5 m high. Several acoustic quantities were measured:  $L_{AFmin}$ ,  $L_{Aeq0,5s}$ ,  $L_{AFmax}$  and the third-octave sound level spectrum. Main conclusions from 3.66 m distant sensor emphasize that:

- At idle, the main differences occurred between cars with engine on and cars with engine off, rather than between HEV and ICE. When off, noise levels were too low to be assessed out of background noise.
- At 10 km/h, maximum sound levels for HEVs are 1 to 9 dB(A) quieter than for their ICE counterparts. At higher speeds, the differences decrease, and are insignificant above 32 km/h in any case since engines are generally running and rolling noise begins to dominate.
- When accelerating, authors conclude that the differences between HEVs and ICE cars are narrow.
- During deceleration, sound level differences are generally narrow.
- At low speed, HEV spectra have lower high frequency contribution, although the Prius may have a 5 kHz spectral peak.

As a complement to the authors' comments, some figures show, however, that the maximum sound level of one accelerating HEV may be 2 dB(A) larger than the corresponding ICE. Even if some HEVs produce somewhat lower noise than ICE under deceleration, one HEV proves to be slightly noisier.

The main objective of (Kim, 2012) was to study the detectability of vehicles equipped with an artificial sound system. As an intermediate outcome, it provided noise levels emitted by a midsize HEV sedan in electric mode, as well as by the same make and model ICE sedan, both without sound system. The measurement protocol was not detailed. When measured stationary and at idle in an anechoic room, 2 metres in front of the vehicle, the HEV was 6 dB(A) quieter than the ICE car. Pass-by sound levels were given for the vehicles driving at the constant speed 15 km/h on a test track, measured with a microphone at a height of 1.2 m and located 2 m from the vehicle centre: both vehicles radiate about the same noise levels.

Studies available on heavy vehicles are scarce. In their study examining internal and external noise emission by hybrid buses and the perception and acceptance of these vehicles by passengers, Bierman and Ruschmeyer (2012) investigated the external noise emission when two diesel and five hybrid (sometimes in electric mode) buses were leaving a bus stop from 0 to 25 km/h. They used an artificial head for recording. The main observations indicate that, considering time histories, hybrid buses have generally reduced peak noise levels relatively to diesel buses during the manoeuvre, but some hybrid buses may be as noisy as the diesel ones (see Figure 8). However, the reduction is actually significant in all-electric mode.

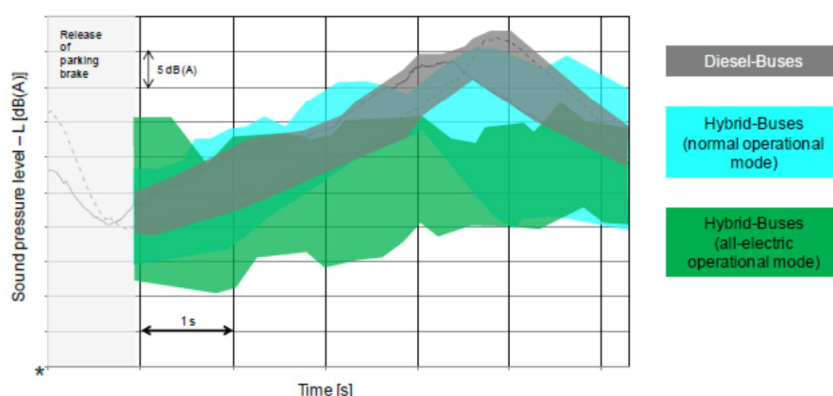


Figure 8: Time history of sound pressure levels from diesel and hybrid buses leaving a stop, measured with an artificial head (unspecified distance). The figure is taken from (Biermann, 2012).

### 3.2 Noise emission data relevant for impact noise studies

The knowledge of external noise emission radiated by any vehicle category is essential for noise impact studies. The total noise is generally decomposed in two components: the powertrain noise and the rolling noise. The sound power levels corresponding to each component are required for EVs and HEVs. To this end, several approaches can be used and are successively presented below: on-board measurement or pass-by measurement.

#### Approach using on-board measurement

Several studies conducted in the Netherlands shared a common approach to investigate traffic noise and urban noise reduction, assuming the traffic to be composed of hybrid (resp. electric) vehicles. One major step was the estimation of speed dependent models for the noise emission of hybrid and electric vehicles, as composed of a propulsion noise component and a rolling noise component. These models were inferred from on-board noise

measurements performed under the hood, combined with European models already available for conventional engine vehicles (like Harmonoise-IMAGINE or CNOSSOS-EU). This also required some assumptions mentioned below.

Verheijen et al. (2008) focused on noise emission from hybrid vehicles, relying on a close national study by DGMR. Measurement involved a microphone placed under the hood of a hybrid Toyota Prius. Recordings were performed along urban and expressway routes. It seems that measures with deceleration were used to determine the rolling noise component, whereas the powertrain noise component was deduced from the measures with acceleration after correction by the above rolling noise, both under the hood<sup>11</sup>. Then, the difference between these two components was identically transferred to external counterpart components, using the model available from the European project Harmonoise-IMAGINE for powertrain noise of conventional cars and assuming the rolling noise to remain unchanged<sup>11</sup>. This approach relies on several uncommented premises, concerning the estimation of propulsion noise and rolling noise under the hood and the assumption of equally internal and external component differences. The same differences were also stated as being valid for inferring external noise emission from medium and heavy trucks. Thus in any vehicle category, noise reduction from an HEV compared with an ICE vehicle was estimated at almost 7 dB(A) at 10 km/h, while being powered only electrically (see Figure 9). It decreased with increasing speed and was about 2 dB(A) at 30 km/h. Noise reduction became insignificant above 50 km/h.

The previous study was completed with electric vehicles in (Verheijen, 2010). Using IMAGINE results in any vehicle category, propulsion noise was assumed to be 10 dB(A) quieter for an electric motor than for a combustion engine, whereas the rolling noise was unchanged. Thus, electric passenger cars appeared to introduce an additional reduction of 1-2 dB(A) to those already provided by hybrid light vehicles at low speed, while for heavy duty vehicles the total reduction from conventional engine trucks could reach 10 dB(A) at 10 km/h (see Figure 9).

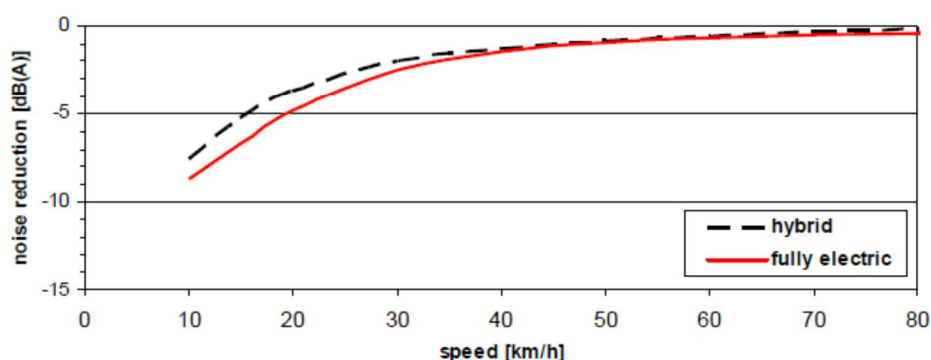


Figure 9: Estimated noise reduction for hybrid and electric passenger cars at pass-by as compared with conventional engine passenger cars. The figure is taken from (Verheijen, 2010).

Within a national program for improving environmental conditions, the issue of traffic noise was reported in (van Leuwen, 2010). In addition to considering driving behaviour as an influencing factor for vehicle noise emission, the reduction potentials by hybrid vehicles was examined. It used the above data relating to the hybrid Prius measured in 2008, and compared it with similar measurement performed under the hood of two conventional engine cars. A much wider spread of noise levels on the hybrid car than on the engine cars was

<sup>11</sup> Subject to correct understanding of the text in Dutch by this report author.

noticed. No external noise emission data was provided. The author concluded that a hybrid car could result in 6 up to 8 dB(A) noise reduction in comparison to combustion engine cars at low speed.

The same approach was deepened in (Jabben, 2012), which investigated noise reduction by a significant amount of hybrid or electric vehicles through various fleet scenarios, combined with silent tyres or a silent road surface. A speed dependent model of mid-size hybrid passenger cars was determined by using the above Prius measurement performed under the hood. A similar procedure was applied to a conventional diesel VW Passat. In each case, noise was recorded under the hood as the vehicles covered specific urban routes, and sound pressure levels were averaged in 5 km/h speed classes. The noise level differences between both cars were considered as being representative of propulsion noise difference and were assumed appropriate also for external propulsion noise emission. Thus, the external hybrid cars propulsion noise component could be deduced from the model available for conventional cars in CNOSSOS-EU, also assuming that the Prius is representative of all hybrid cars. Sound power levels are shown in Figure 10: the electric motor worked alone on the hybrid car at low speed, and the engine was also running at medium speeds leading to a constant propulsion noise difference between both vehicle types.

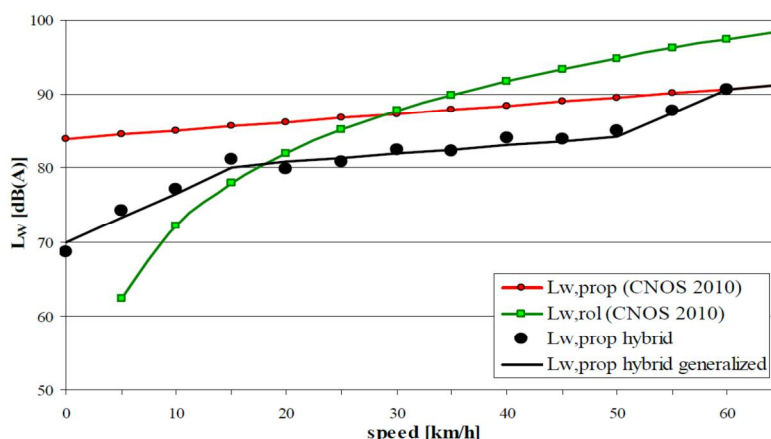


Figure 10: Sound power level of the noise propulsion component and the rolling noise component at constant speed provided by CNOSSOS-EU for a conventional engine passenger car, and estimated propulsion noise component of a hybrid car. The figure is taken from (Jabben, 2012).

In parallel, the case of electric cars was studied through the external noise measurement of two subcompact passenger cars: an electric Nordic Th!nk City and a conventional diesel engine VW Polo. Noise levels were recorded at pass-by on a road with a dense asphalt concrete surface, with a microphone 3 m from road axis and at a height of 1.5 m. The noise reduction introduced by the electric car with respect to the non-electric one is shown in Figure 11. The authors note that the relatively heavier diesel car may lead to an overestimated noise benefit. They also think that the powertrain noise from electric cars could be disregarded in traffic noise assessments.

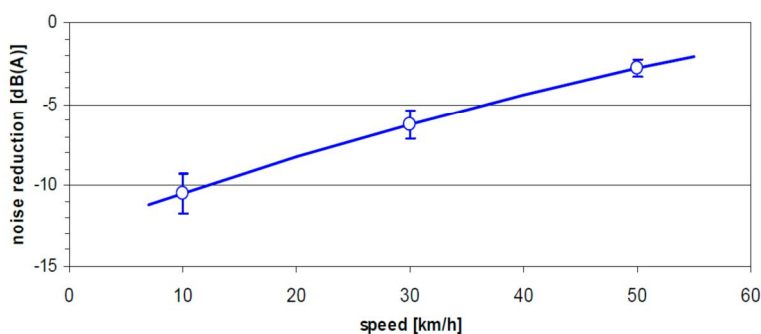


Figure 11: Total noise reduction for the electric Nordic Th!nk City as compared with a conventional diesel VW Polo at constant speed pass-by, measured at 3 m from the lane axis and a height of 1.5 m. The figure is taken from (Jabben, 2012).

### Approach using measurement at pass-by

Noise measurements at vehicle pass-by generally involve standardized procedures. However other methods using microphone arrays are sometimes implemented to identify and describe the main noise sources on the vehicles. Among the various studies available in the literature, a great part relates to light vehicles and a few consider heavy vehicles. For an easier reading, this subsection is arranged from lightest to heaviest vehicles, beginning with quadricycles, continuing with passenger cars which form the widest category, in logical accordance with the actual green vehicles market and fleet, and ending with buses and trucks.

#### *Quadricycles*

In relation with the Italian postal services and the development of sustainable delivery, a noise assessment of hybrid and electric quadricycles was conducted. It concerned a light quadricycle Ducati Free DUCK with a maximum speed of 45 km/h, existing in two versions (one electric with a 50 km range, and one series-hybrid extending the range to 200 km), which may be driven with a moped license. The hybrid version may optionally be operated in all-electric mode. The first electric version was acoustically evaluated and compared with a traditional two-wheel motorcycle (Cotana, 2008), completed later with the hybrid version of the quadricycle (Cotana, 2009). Finally, updates of the two versions were made with the implementation of an energy recovery system. Goretti et al. (2012) gathered the acoustical assessment of the various versions, performed in accordance with European Regulation for the approval of four-wheel vehicles and, as such, implementing the standard ISO 362-1.

Measurement involved a microphone located on the trackside 7.5 m away from the track centre and at a height of 1.2 m. The maximum noise pressure level was recorded during acceleration on a 20 m long test area; accounting of the vehicle speed ability, the quadricycle arrived at 30 km/h at the area entrance and then accelerated strongly in order to reach the output speed target 40 km/h, actually 35 km/h. In these conditions, the electric version turned out to be about 3.5 dB(A) quieter than the hybrid version, in itself quieter than the conventional two-wheeler by about 10 dB(A).

#### *Light motor vehicles*

The first studies on the noise emission from hybrid and electric cars just followed the serial production of hybrid and electric light vehicles in the late 90s. In 2001, Lelong et al. provided the assessment of the noise emission of a Toyota Prius I, both in hybrid and electric mode, and an electric Citroen AX compared with a diesel-powered AX, on a dense asphalt concrete

0/10 test track (Lelong, 2001). Considering A-weighted maximum noise pressure levels measured at pass-by in accordance with the French standard NF-S-31119-2:

- The electric AX and the Prius I in electric mode were acoustically equivalent and provided the quietest performance. The maximum noise level at 7.5 m increased linearly with the logarithm of the vehicle speed  $v$  (km/h) according to the equation  $L_{Amax}=75.9+34.7 \times \log(v/90)$  for the Prius I in electric mode.
- When driven in hybrid mode (engine and electric motor working), the Prius was 5-6 dB(A) noisier than in electric mode at low speed. In this mode the maximum noise pressure level at 7.5 m increased according to the equation  $L_{Amax}=75.2+27.2 \times \log(v/90)$ .
- Both modes were equivalent above 60 km/h as rolling noise dominated (see Figure 12).
- As for the diesel AX, the noise emission depended highly on the selected gear.

The noise reduction of the Prius hybrid mode compared with the diesel car in 1<sup>st</sup> gear was about 10 dB(A) at low speed (resp. 3.5 dB(A) in 2<sup>nd</sup> gear), whereas the electric mode reduced the noise level by 15 dB(A) with respect to the 1<sup>st</sup> gear (6-8 dB(A) in 2<sup>nd</sup> gear). This underlines the large benefit which can be expected from these vehicles on road sections with restricted speeds. At medium speeds, the hybrid car behaved like the conventional diesel vehicle in 3<sup>rd</sup> gear. At speeds larger than 50 km/h, all vehicles were acoustically equivalent, since the rolling noise was the leading noise source. Finally, the Prius under strong acceleration increased noise levels up to 4 dB(A) relatively to the constant speed hybrid mode.

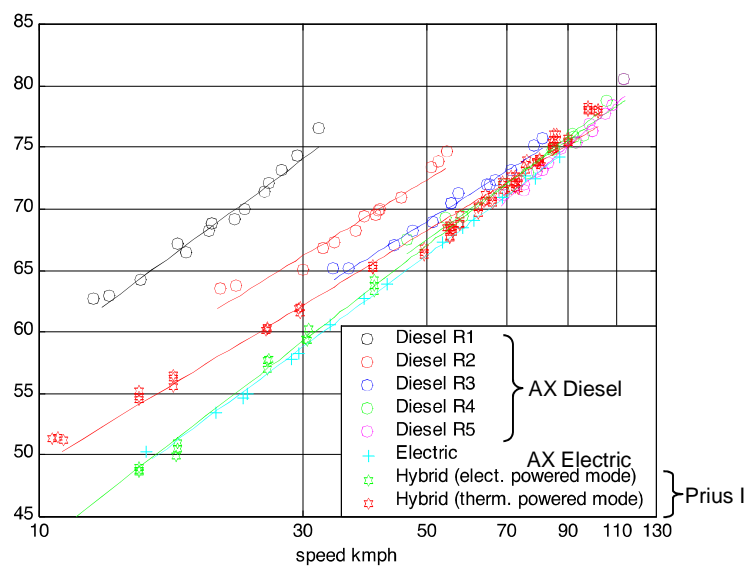


Figure 12: A-weighted maximum noise pressure level measured at constant speed pass-by for the Toyota Prius I (hybrid/electric mode), the electric Citroen AX, and the diesel Citroen AX (5-speed transmission R1 to R5), measured on a microphone at 7.5 m and 1.2 m height. The figure is taken from (Lelong, 2001).

Similar measurements, performed more recently by the same team in identical conditions, were applied to an electric Peugeot 106, at constant speed and with several acceleration rates (see Figure 13). The maximum sound pressure level at 7.5 m increased, with speed  $v$  in km/h, as  $L_{Amax} = 76.9 + 35.7 \cdot \log(v/90)$ , which is barely larger than the previous electric AX. Acceleration increased noise emission only slightly at low speed. The data relative to the Prius I, the electric AX and the electric Peugeot 106 is available for the next tasks of Work Package 2.

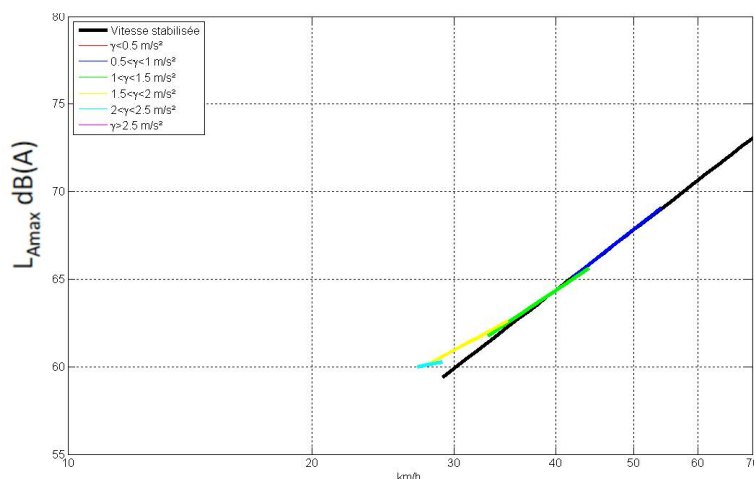


Figure 13: A-weighted maximum sound pressure level at constant speed pass-by (black curve) and under several acceleration rate (colour curves) for the electric Peugeot 106, on a microphone at 7.5 m and 1.2 m height [source IFSTTAR]

The study reported in (Yoshinoga, 2009) focuses on the impact of electric vehicles on traffic noise in Japan. The authors determined the sound power level at pass-by from a small electric vehicle (2 seats) and a medium hybrid passenger car in all-electric mode, using a microphone at standard position (distance 7.5 m, height 1.2 m) and performing measurement at constant speed, slow and full acceleration. Sound levels were recorded at the time the vehicle centre passed in front of the microphone; thus it may slightly differ from the maximum sound levels. Main conclusions pointed out that the noise emission from the electric vehicle was similar at constant speed and under acceleration, contrary to conventional vehicles for which acceleration increases noise. Comparing with data available in Japan for conventional engine vehicles under acceleration, the authors reported a sound power level reduction of 10 dB(A) at 30 km/h and 4 dB(A) at 60 km/h. They emphasized the potential noise reduction which may be expected from fleet electrification, mainly near intersections.

Arguing on the quietness of electric and hybrid vehicles and potential safety risks by other road users, some authorities encourage the use of alerting sounds on these vehicles in low speed condition. However, some authors worry about the effect on noise, which goes against the efforts to decrease traffic and urban noise, whereas safety risks would not be clearly proved. To support their argumentation, Sandberg et al. (2010) provided some quantitative vehicle noise data. They provided brief information on a comparison performed by the Belgian Road Research Centre on a Toyota Prius, either in hybrid or electric mode, around 20 km/h. Measurement conditions are not documented. The difference between both modes appeared to be very low at 20 km/h. Since the vehicle was equipped with quiet tyres, the authors concluded that the rolling noise was the main noise source in this case. This result does not agree exactly with those given in Figure 12 on a previous Prius version, which showed a 4 dB(A) increase from the electric to the hybrid mode at 20 km/h, with the extra contribution of the engine in the latter case.

On request of the Department for Transport (DfT) in Great Britain, the Transportation Research Laboratory (TRL) carried out a study on the risk perception of quiet vehicles by visually impaired pedestrians (Morgan, 2011). It included a noise assessment of four ICE vehicles and four quiet vehicles (one hybrid and three electric vehicles, all mentioned below as E/HE vehicles) of various sizes with a mass not exceeding 3.5 tons, for driving speeds up to 50 km/h. Only some selected measurement conditions are reported here. Sound



measurements were performed along a test track with a 14 mm Stone Mastic Asphalt surface, classified by the authors as a low-noise road surface. Microphones were placed on the track side 7.5 m and 1.8 m from the running lane centre, both at a height of 1.2 m and the first one being in accordance with standard ISO 11819-1:2001 specifications. The maximum sound pressure levels at vehicle pass-by were recorded at several constant speeds: 7-8 km/h, 20 km/h, 30 km/h and 50 km/h. At the lowest speed, background noise was not insignificant and affected vehicle noise measurement. Excluding one ICE vehicle definitely behaving as an outlier, the noise level range of the E/HE could not be strictly distinguished from the ICE vehicles over the test speed range, since the quietest and the loudest vehicles belong to ICE category, as it may be observed in Figure 14. Notice that in this figure, as the measurement distance was 1.8 m, the noise levels cannot be directly compared with these on Figure 12 for instance. On the average, ICE and E/HE vehicles radiate quite similar noise levels towards this microphone position. Spectrum analysis pointed out that noise spectra did not clearly differ for ICE and E/HE vehicles, except for the presence of low frequency peaks associated with the exhaust system on the ICE cars. A second test involved pull-away from rest. In this case only measurement at 1.8 m distance was performed. Again, maximum levels from both vehicle technologies were rather similar, the E/HE cars with low acceleration being only 1 dB(A) quieter on average, and comparable at high acceleration rate. However, vehicle ranking can vary slightly when considering greater propagation distances like 7.5 m; this item is deepened in the next tasks of FOREVER project. The data from this study is available for Work Package 2.

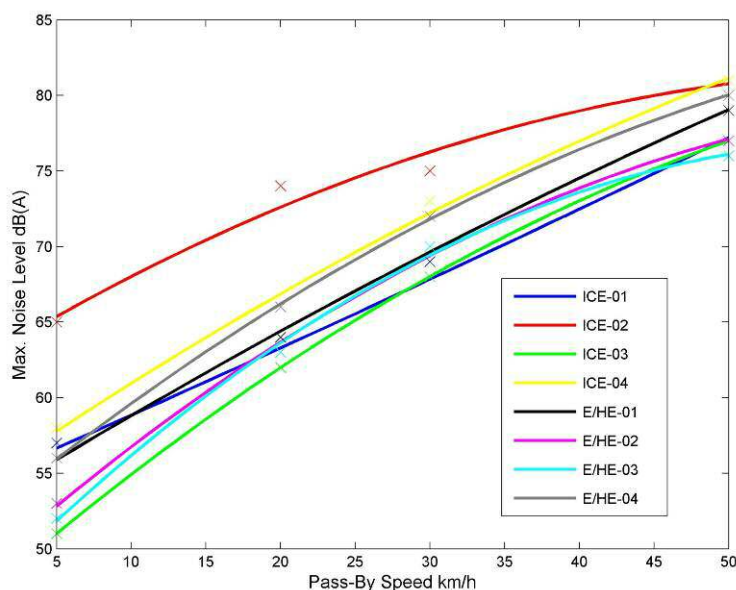


Figure 14: A-weighted maximum sound pressure level measured at constant speed pass-by for four ICE and four E/HE vehicles, measured on a microphone at 1.8 m distance and 1.2 m height. The figure is reproduced from (Morgan, 2011) with permission of TRL Limited.

The European Community funded the project City Hush (2010-2012), which dealt with Acoustically Green Road Vehicles and City Areas and aimed at providing city administrations with solutions and tools for reducing noise in city environments. Acoustically green vehicles were one main item of the project. Several tasks involved investigations and measurement with electric or hybrid vehicles. The most appropriate study within the scope of FOREVER is reported in (Stenlund, 2011-2). It aimed at defining noise criteria for vehicles to access quiet zones in cities, labelled as Q-zones. An experiment was conducted to measure noise emission by four electric vehicles and an electric hybrid (Toyota Prius) and derive the powertrain noise and rolling noise components. The Prius was driven in electric mode under

25 km/h. The four electric vehicles were: Mitsubishi iMiEV, Fiat 500 EVadapt, Peugeot iOn, Citroen C-Zero. It should be noted that Mitsubishi iMiEV, Peugeot iOn and Citroen C-Zero are actually identical vehicles, resulting from a partnership between Mitsubishi and PSA Peugeot Citroen. Noise measurement was performed according to standard ISO 362-1:2007, on a test track with dense bitumen asphalt road surface and a maximum stone size 8 mm (ABT 8). No information is given on the background noise. In this experiment, standard pass-by configurations were extended and included:

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

The procedure used to separate driveline noise and rolling noise from the total noise at constant speed is the following:

- the A-weighted maximum noise pressure level for the rolling noise follows the equation  $m \log v + c$ , where  $m$  and  $c$  are constant parameters for each vehicle and  $v$  is the speed,
- the  $L_{Amax}$  for the driveline noise follows also the same expression  $L_{Amax} = m' \log v + c'$ , where  $m'$  and  $c'$  are constant parameters specific to each car; this equation should be appropriate for automatic or one gear transmission vehicles according to the author,
- the rolling noise is determined with the use of the high speed measurements,
- the driveline noise is deduced by fitting the above law to the measured data, considering the total noise as {rolling noise + driveline noise}

For the wide-open-throttle tests, the report specifies that the procedure is similar to constant speed pass-bys, except that the rolling noise under acceleration is assumed to equal the constant speed rolling noise increased by 2 dB(A). However this procedure remains unclear since it does not agree with the figures provided for each accelerating vehicle. From the figures, it can be inferred that the authors suppose the driveline noise to be a constant and the rolling noise to increase linearly with  $\log v$ .

As expected, the i-MiEV, the C-Zero and the iOn behaved quite similarly at constant speed and provided very close rolling noise components. They proved to be the quietest cars of the test whereas the Fiat 500 was the noisiest, the Prius being only slightly below (see Figure 15). The extent from the quietest to the noisiest did not exceed 6 dB(A), of the same order than in Figure 14. Since the driveline component is comparatively small, its estimate could be somewhat inaccurate. However, when compared with the results from other experiments (for instance Figure 12 or Figure 13), the noise levels provided in CityHush clearly appear smaller by 5-7 dB(A) at the least.

Under acceleration the noise levels increase strongly compared with constant speed. The electric Fiat 500 is the quietest at 20 km/h but the noisiest at 50 km/h. Stenlund (2011-2) points out that the driveline noise is dominant for every vehicle, except for the Fiat 500. However, the assumption of a constant driveline noise component might be inappropriate, at least for this vehicle, and the component separation may be incomplete. Due to rolling noise contribution at 50 km/h, (Stenlund, 2011-2) recommends to perform wide-open-throttle 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.

Finally, although microphone array measurements were mentioned in CityHush project, for instance in (Telle, 2012), in order to separate and describe the relevant noise sources on the vehicles, no result is available in the public reports.

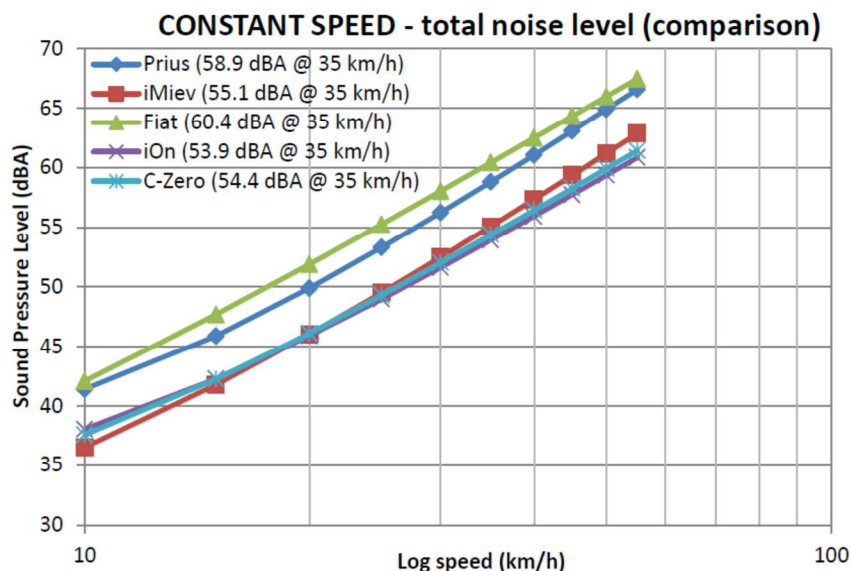


Figure 15: Models of maximum sound level at constant speed pass-by for the five green vehicles measured in CityHush project, at standard position 7.5 m, estimated from measurement in the speed range [15 km/h – 50 km/h]. The figure is taken from (Stenlund, 2011-2).

In the United States standardized sound emission levels, referred as “Reference Energy Mean Levels” (REMEL), are available for the various vehicle categories from motorcycles to heavy vehicles, in order to be used in traffic noise prediction or soundscape studies. These levels have been specified for conventional engine vehicles in third octave bands as a function of speed, for cruise-by or full throttle. Kaliski et al. (2012) determined the REMEL coefficients for an electric vehicle. As such, they meet one of the objectives of the project FOREVER. In their study they investigated the noise emission of a Chevrolet Volt in all-electric mode. This car, although often presented as a plug-in electric vehicle, is actually an electric hybrid car, operating either electrically, or as a series hybrid when the vehicle is powered only by the electric motor(s) and the engine is used as a generator to supply electricity, or even as a series-parallel hybrid in some cases where both the electric motor and the engine power the vehicle while the engine supplies also electric energy. In Europe the Opel Ampera is the equivalent. Kaliski (2012) measured the noise emitted by the Chevrolet Volt on two roads, either at constant speed or full-throttle, from 8 to 113 km/h by 8 km/h steps. Two microphones were used, respectively located 7.5 m and 15.2 m from the lane centre with discontinuous ground surface between the road and the microphones. 1second-equivalent noise levels were recorded in third-octave bands and the REMEL coefficients were calculated for the Volt. Global noise levels were provided at steady speed and with acceleration and were compared with the REMEL data available for conventional ICE automobiles (see Figure 16). Although not clearly specified in the article, the microphone distance in these figures was probably 15 m. It is observed that the electric vehicle was quieter than ICE cars under 24 km/h and over 64 km/h at steady speed, and under 40 km/h with accelerating vehicles. Otherwise, both vehicle types radiated similar noise levels. Considering spectra, apart from the global level differences already observed, the noise radiated by the Volt had lower contribution in low frequencies at steady speed and under acceleration.

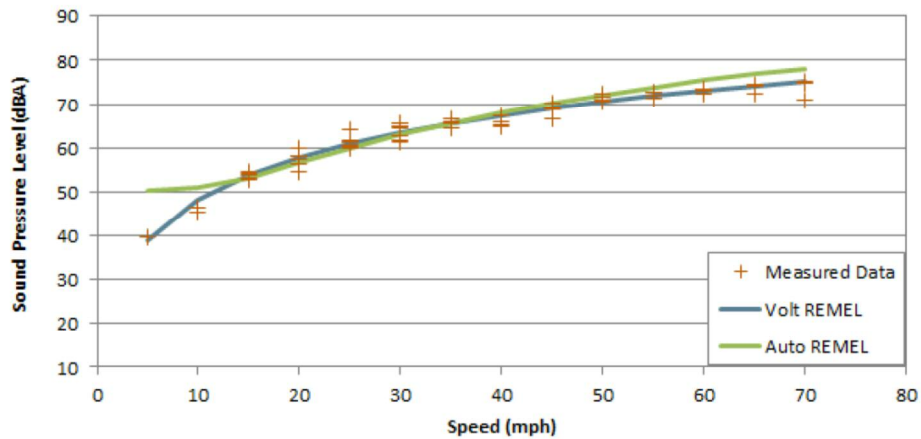


Figure 16: Sound pressure levels  $L_{Aeq,1s}$  and calculated REMEL curve for the Chevrolet Volt in cruise mode, and standardized REMEL curve for automobiles. The figure is taken from (Kaliski, 2012).

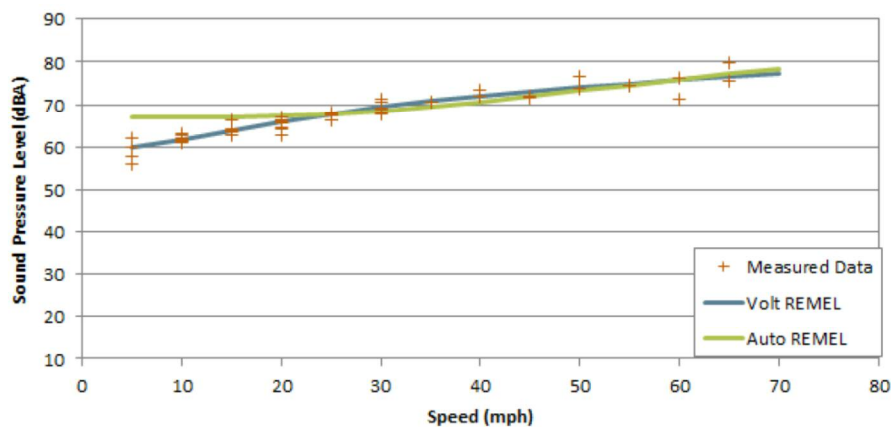


Figure 17: Sound pressure levels  $L_{Aeq,1s}$  and calculated REMEL curve for the Chevrolet Volt in full-throttle mode, and standardized REMEL curve for automobiles. The figure is taken from (Kaliski, 2012).

### Heavy duty vehicles

Truck manufacturers gradually include environmentally-friendly truck models in their range. Although still limited, their expansion in the vehicle fleet increases, supported by access restrictions in some city areas. The ranges concerned include either medium duty trucks, using mostly parallel hybrid technology but tests are currently undertaken with serial hybrid demonstrators, or light delivery electric trucks. Little data is available on the noise emitted by these new technology trucks. An assessment was recently conducted on a parallel hybrid rigid truck, considering noise emission in hybrid mode and in electric mode and exploring most real use driving conditions: steady speed, acceleration and deceleration with braking (Pallas, 2014). In addition to maximum noise levels at 7.5 m, the noise sources were investigated with a microphone array, as well as the radiation directivity of the vehicle in a vertical plane. Results were compared with an equivalent conventional engine truck. The road surface of the test track was dense asphalt concrete 0/10. At constant speed the truck in hybrid mode turned out to reduce noise by 1-3 dB(A) depending on speed and gear

selection. This reduction, introduced by the powertrain, remains relatively limited since the engine is still involved as a powering element, like in the ICE truck. But the reduction was particularly significant in the electric mode where the noise benefit reached -8 dB(A) at low speed. This benefit cancelled above 50 km/h as the rolling noise was the leading source, with an extra contribution of the drive wheels (rear axle) in comparison to the steering wheels (front axle).

The noise increase under strong acceleration was also investigated below 50 km/h: while the powertrain (engine, exhaust) was the dominant source both on the ICE truck and the hybrid truck in hybrid mode, the drive wheel noise contribution was the most significant source in all-electric mode over the whole speed range. Global noise levels under acceleration were significantly lower in electric mode compared with the ICE truck over the speed range tested, and reached about 6 dB(A) below 20 km/h. As for braking situations compared with constant speed, whereas braking introduced little or few noise increase for the ICE truck, the slightly larger raise observed on the hybrid truck was attributed to the motor in regenerative mode. Nevertheless, the electric mode remained the quietest operating mode, with up to 3 dB(A) reduction in comparison to the braking ICE truck over the test speed range.

Finally, in all driving situations the truck in electric mode was observed to radiate even lower noises towards upward directions. Hence, the noise benefit from the electric mode was still larger for dwellers living in upper storeys.

#### *Road public transport*

All-electric road public transport have been in use for a long time within cities with trolleybuses, compelled to predefined routes due to the electricity supply by wires. For several years bus manufacturers have been developing innovative “green” concepts for their bus range. The widest offer concerns hybrid electric buses, most of them being equipped with series hybrid technology. An increasing number of transit authorities include hybrid buses in their fleet. Another avenue explored by manufacturers concerns plug-in electric buses, suppressing the unsightly wire network necessary to grid connection: battery packs store the electrical energy and can be quickly recharged at specific bus stops or route ends.

The noise emitted by an articulated trolleybus was measured at pass-by in (Lelong, 2007), using 5 microphones distributed on an arc of circle in order to calculate the sound power level of the running vehicle, and an additional microphone at standard position 7.5 m from the lane axis and 1.2 m high. The road surface was asphalt concrete. Several operating conditions were studied at constant speed from 20 to 40 km/h:

- the electric mode which is the normal operating mode, measured without the air-conditioning system,
- the engine mode, which is a degraded mode in case of electric power failure.

The engine mode introduces a noise level increase of 3 dB(A) around 20 km/h, on the 7.5 m distant microphone. No difference was observed at 30 and 40 km/h. According to further noise measurement conducted with the air-conditioning system on the vehicle at stop, the contribution of this system turned out to be insignificant at the 7.5 m standard position when the trolleybus passes by in the speed range tested. Since this system is placed on the vehicle roof, its influence should be higher at upper measuring points.

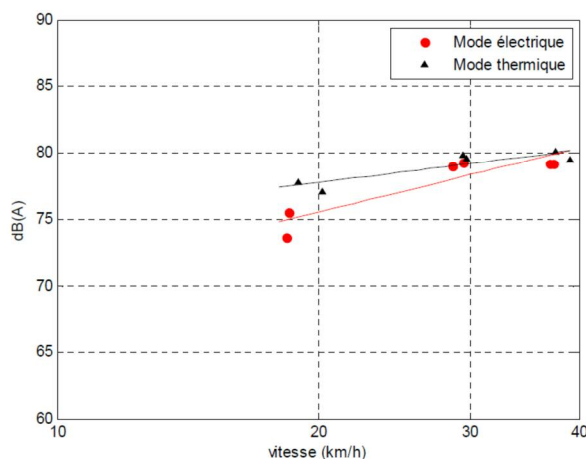


Figure 18: A-weighted sound pressure level at constant speed pass-by of a trolleybus, measured at 7.5 m distance and 1.2 m height, in electric mode (red) and in degraded engine mode (black). [source IFSTTAR]

The assessment of the noise emission from several buses available in the USA, involving various propulsion technologies and vehicle length (axle number), has been carried out in (Ross, 2007). Leaving out compressed natural gas buses which are out of the present scope, it turns out that the noise difference between diesel-electric hybrid and conventional buses in usual idling conditions is not very significant, nor is it under full-throttle acceleration. No electric bus is included in this idling and acceleration comparison. However, considering constant-speed pass-bys, electric trolleybuses at 48 km/h (30 mph) are 10 dB(A) [resp. 7 dB(A)] quieter than the conventional [resp. hybrid] buses. Whereas the difference between hybrid and conventional buses become less marked at 64 km/h (40 mph), the electric trolleybuses are still 4 to 5 dB(A) quieter. There is no indication on the road surface of the test sites.

### 3.3 Summary of findings of the literature review on EV and HEV noise emission

#### Concerning the methods used to evaluate noise emission from EVs and HEVs:

The studies motivated by perceptive outcomes carry out specific experiments, generally out of any standard procedure, only occasionally with some common features. Consequently, quantitative results cannot be strictly compared from one study to the other. These studies generally consider noise emission from the pedestrian viewpoint and hence perform measurement at short distance from the road lane (i.e. kerbside), in low speed driving conditions which can be met and potentially become hazardous in road crossing situations.

The studies motivated by noise impact outcomes for dwellers rely either on on-board measurements or on roadside measurements:

- The few “on-board studies” involve noise measurements performed under the hood to derive the on-board powertrain component. On-board differences observed between EVs/HEVs and ICE vehicles are identically transferred to roadside noise levels provided by models available for conventional vehicles (i.e. Harmonoise or CNOSSOS-EU). This approach implies several shortcuts and assumptions, and should be restricted to rough estimates.

- Most studies involve measurements with roadside microphones at standard position (distance 7.5 m and height 1.2 m in Europe) and pass-by procedures complying with international standards (ISO11819-1 at constant speed, ISO362-1 in acceleration). These standard specifications are extended to pass-bys performed over a wider range of operating and speed conditions.
- Some studies complete the previous standard approach with microphone array measurements, providing information on the main noise source areas on the vehicle and their behaviour with various operating conditions.

### **Concerning the experimental conditions:**

One crucial point for the measurement of the noise emission from quiet vehicles is the background noise, which may limit the validity of the noise measures at low vehicle speed and is still more critical in some frequency bands. Even situations usually considered as quiet might be too noisy in this context.

Information on the type of road surface is generally not available in perceptive studies. It is available most of the time in the roadside noise impact studies: various surfaces are used, depending on the current surfaces in the concerned country.

Depending on studies, driving situations at steady speed, under accelerating or braking are investigated.

### **Concerning the vehicles:**

Most studies are devoted to light vehicles, which is consistent with the vehicle category distribution of EVs/HEVs already on the road. Some recent studies have investigated noise emission from heavier vehicles, motivated by the widening offer of manufacturers and technological innovations in these categories. The experiments often rely on noise comparisons between the selected EVs/HEVs and equivalent ICE vehicles.

Makes and models are not always specified for confidentiality reasons and because of sensitive information in a competitive market.

Relative to hybrid light vehicles, most vehicles investigated in the noise studies use the series-parallel hybridization, which is the most widespread technology, and above all the Toyota Prius. A few others are parallel hybrid vehicles.

Relative to pure electric light vehicles, subcompact cars are the only cars investigated. However larger vehicles are now available on the market.

### **Concerning the noise emission of EVs and HEVs light vehicles:**

As a general rule, studies are mainly focused on low speeds, since this speed range is the most likely to provide differences with conventional ICE cars. At high speeds all agree and assert that all vehicles behave similarly, since rolling noise is the dominating source, but there is no consensus on the lower bound (from 15 to 50 km/h). Otherwise, the studies available in the literature provide mixed conclusions.

At constant speed, most authors conclude that EVs and HEVs, the latter as far as no engine is working, are quieter than ICE cars at idle, with a noise reduction between -5 and -20 dB(A). The difference amounts to -1 to -10 dB(A) at 10 km/h and vanishes above 20-30 km/h. However, other studies show that on average there is no substantial difference

between EVs/HEVs and ICE cars on the whole speed range, some ICE cars being as silent as – or even quieter than – electric vehicles.

Some studies notice only small noise level differences when comparing EVs and HEVs under acceleration with steady speed, while others point out an increase of more than 15 dB(A). Similarly when comparing accelerating EVs/HEVs to accelerating ICE cars, differences range from no difference at all up to a 10 dB(A) reduction.

It is sometimes noticed that data measured on hybrid vehicles are scattered around an average trend for any given operating condition. This observation, also confirmed by car manufacturers, might result from a variable balance between the engine load and the motor load depending on multiple internal factors in addition to the speed request.

### **Concerning the noise emission of EVs and HEVs heavy vehicles:**

Few studies are available on hybrid and electric heavy vehicles. Measurements conducted at constant low speed on a parallel hybrid heavy truck showed that the noise reduction was limited (1-3 dB(A)) between a conventional ICE truck and the truck in hybrid mode, whereas there was quite a significant noise reduction (8 dB(A)) when driving in electric mode. Thus, the significant noise breakthrough occurred between hybrid and electric mode on the parallel hybrid vehicle. A similar behaviour has been noticed in a study involving buses.

The noise emission rises significantly for the accelerating trucks. The noise benefit introduced by hybridization is reduced under acceleration, even if the electric mode still has an advantage. Braking situations, activating the energy recovery system and loading the electric motor, increase vehicle noise emission when compared with steady speed.

These trends observed on a small amount of vehicles need to be confirmed through other measurement campaigns.

### **Concerning the noise emission of all quiet vehicles:**

Whatever the vehicle type and technology, the noise emission of quiet vehicles at nearly all steady speeds is dominated by the rolling noise, whose contribution still increases in acceleration and braking situations through torque influence in the tyre-road contact area. Consequently, the implementation of low-noise tyres and/or low-noise road surfaces is a key issue for noise emission of these quiet vehicles.



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## 4 Noise emission data on electric and hybrid electric vehicles

One objective of the project FOREVER is to characterize the noise emission of EVs and HEVs. Ideally, the assessment should include all vehicle categories and, in each category, the variety of technologies available on the road, in a statistically representative way. Within the context of the project, this assessment inevitably remains limited. A dataset is already available from the project partners. It has been completed by additional experiments, which focused on three vehicles selected in order to widen as far as possible the vehicle types and technologies investigated: one electric car of category M1, one hybrid car of category M1 and one electric truck of category N2.

This section first presents the experiment and details the noise emission results from the three vehicles tested. In a second part, this data is merged with data already available by project partners and main conclusions on EV and HEV noise emission are drawn.

### 4.1 Experiment and results

Three vehicles have been tested in the framework of FOREVER project: a small electric passenger car, a larger hybrid passenger car and an electric truck. Considering the CNOSSOS vehicle categories, both passenger cars belong to category 1 whereas the truck belongs to category 2. Their noise emission has been assessed through pass-bys on a test site, considering a wide range of real use operating conditions: constant speed, acceleration, deceleration and braking. At first, the test conditions and experimental setup are described. Then, the noise emission results are reported for every vehicle. The main findings are summed up in a final subsection.

#### 4.1.1 Test site and experimental setup

The vehicles have been tested on the IFSTTAR test facility located near Lyon, which provides open-field measuring conditions similar to the standard specifications. The test track surface is dense asphalt concrete 0/10. The experiment took place between the end of June and August 2013, in mild or warm temperature conditions (between 20°C and 30°C), the wind speed being smaller than 2 m/s in any case.

Two different measuring devices were implemented: a set of microphones at 7.5 m in accordance with common standards on vehicle noise<sup>12</sup>, as well as a microphone array for noise source analysis.

##### 4.1.1.1 Measurement with 7.5 m microphones

Six microphones separated by 10 metres were located in pairs on both sides of the track, at a distance of 7.5 metres from the track centre and a height of 1.2 metre (Figure 19 and Figure 20). Three infrared cells were distributed at the position of each microphone pair on the track side. They were used to detect reflecting plates placed by pairs on the vehicles, giving information on the vehicle position and kinematic parameters during the experiment. For each vehicle pass-by, the instantaneous vehicle speed in front of each microphone pair was recorded, together with the maximum A-weighted sound pressure level  $L_{Amax}$  on each microphone in octave bands or global levels. The useful frequency range extends up to 12.8 kHz.

<sup>12</sup> For instance EN ISO 11819-1 (2002)



Figure 19: Measurement setup with microphones at 7.5 m

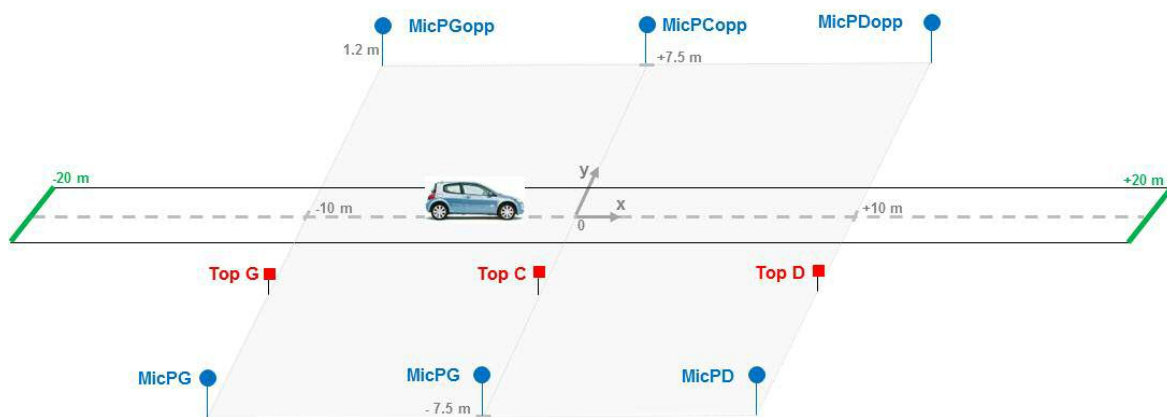


Figure 20: Test arrangement for the measurement with microphones at 7.5 m

#### 4.1.1.2 Measurement with the array

A second equipment involved a 57-microphone plane array to identify the main noise sources on the vehicle (Figure 21). The array processing carries out constant beamwidth beamforming (Ward, 2001), adapted to short-range moving sources and completed by a deconvolution method to compensate for the array pattern. The array diameter is 2.56 m and the measuring distance between the array (located at the roadside) and the side of the vehicle is about 2.7 m, monitored at each vehicle pass-by in order to refine the analysis. Among other things, this setup provides vehicle noise maps as well as estimates of the main noise sources contribution at pass-by. Some clues on microphone arrays and array processing may be found in subsection 2.2 of the review.

An infrared cell is located near the array to detect the vehicle position and determine the vehicle kinematic parameters. A rangefinder is also used to measure the pass-by distance from the microphone plane to the vehicle side, in order to match the focus distance of the beamformed array to each pass-by. The frequency range of the vehicle noise source analysis extends up to 6.4 kHz.

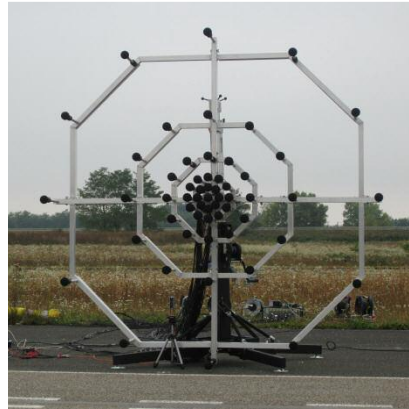


Figure 21: The 57-microphone array

#### 4.1.1.3 Background noise

A critical point for measuring low noise vehicles concerns the background noise level. Most standard procedures recommend disregarding the test values measured at the vehicle pass-by when they do not exceed the background noise level by more than 10 dB, in global levels or even in frequency bands. This specification happens to be very much restrictive for outdoor measurements in the context of quiet vehicles at low speed, in particular in some frequency bands. On the other hand, the standards intended for the “Measurement of Minimum Noise Emitted by Road Vehicles” (SAE, 2012) (ISO, 2013-2) propose to use correction terms when the overall test level lies between 3 dB and 10 dB over the background noise level, whereas the value is removed if the difference is lower than 3 dB (see § 2.3).

We chose to take the recommendations available in these latter standards as a model, but with some adjustment. A correction term was applied to the test value according to the following expression, as long as the difference  $\Delta$  to the background noise level was included between 3 and 10 dB for the global level or between 5 and 10 dB in octave bands:

$$L_{corrected} = L_{test} + 10 \log \left[ 1 - 10^{-\frac{\Delta}{10}} \right] \quad (30)$$

where  $\Delta = L_{test} - L_{bg}$  is the difference in dB between the test result  $L_{test}$  and the background noise level  $L_{bg}$ . If the difference  $\Delta$  is smaller than 5 dB in octave bands and 3 dB on global levels, the test value is disregarded. However, despite these precautions one should be aware that background noise might still slightly affect the lowest noise levels.

Depending on the measurement day and time, the global background noise level lied between 45 dB(A) and 48 dB(A). Figure 22 displays examples of background noise spectra averaged on 10 seconds, recorded on three different days during the experiment. As a consequence, global noise levels are mostly unaffected, whereas a part of the results in the octave 8000 Hz may be removed and to a lesser degree in the octaves 63 Hz and 125Hz.

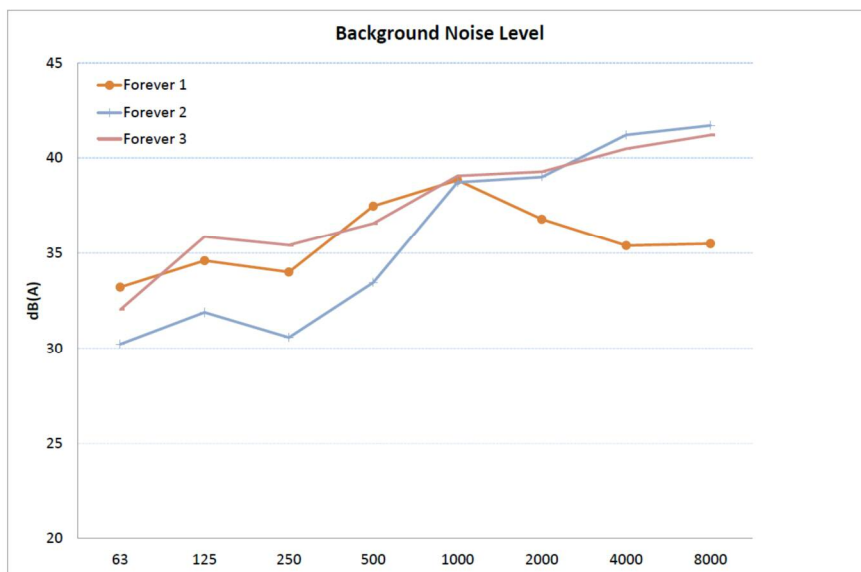


Figure 22: Example of background noise spectra recorded on different days

#### 4.1.2 Noise emission of a small electric passenger car

Supermini cars form a significant part of the electric passenger cars available in the European fleet. The noise emission of a supermini<sup>13</sup> electric car, a Citroen C-Zero, has been assessed in the FOREVER project. This vehicle has a direct transmission and can travel at speeds up to 130 km/h. It was equipped with tyres Dunlop Enasave 2030 of dimension 145/65 R 15 on the front axle and 175/55 R 15 on the rear axle. Microphones at 7.5 m were the only measuring equipment used with the C-Zero.

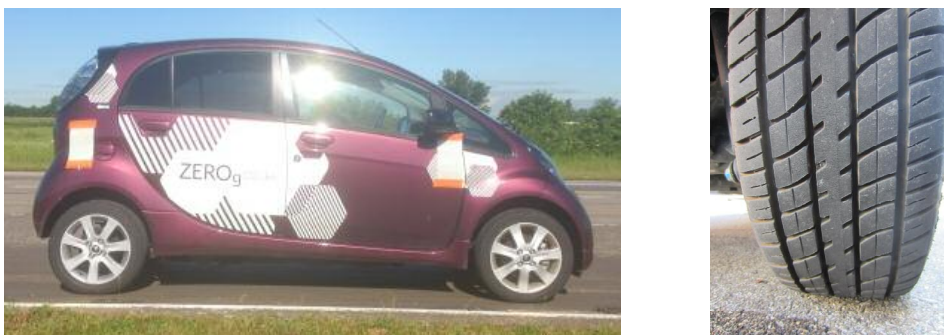


Figure 23: Citroen C-Zero and tyres Dunlop Enasave

Pass-bys were performed at constant speed from 17 to 102 km/h. The global noise level values measured at constant speed are quite concentrated and follow a linear trend on a  $\log(\text{speed})$  scale (Figure 24), described by the following equation:

$$L_{A \max} = 70.1 + 35.0 \log\left(\frac{v}{70}\right) \text{ dB(A)} \quad (31)$$

<sup>13</sup> According to the classification EuroNCAP ([www.euroncap.com](http://www.euroncap.com))

where  $v$  is the vehicle speed in km/h. In the whole speed range, a doubling of the vehicle speed increases the maximum noise level at pass-by by 10.5 dB(A). This behaviour renders simultaneously the rolling noise and the powertrain noise contributions. Due to the direct transmission, the powertrain noise depends directly on the vehicle speed over the whole speed range. Moreover, coast-by is not possible since transmission cannot be released. Thus, rolling noise and propulsion noise cannot be easily separated through this simple pass-by measurement approach without additional information. In frequency, this linear trend remains valid with various slopes from the octave 500 Hz to the octave 4000 Hz at least, but not in the lowest octave bands (Figure 25).

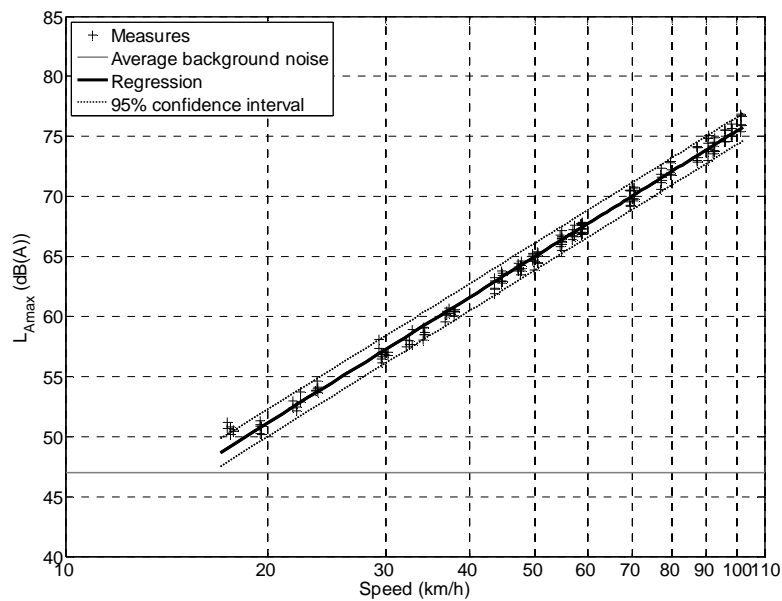


Figure 24 : Global A-weighted maximum sound pressure level of the C-Zero at constant speed at 7.5 m from the track centre

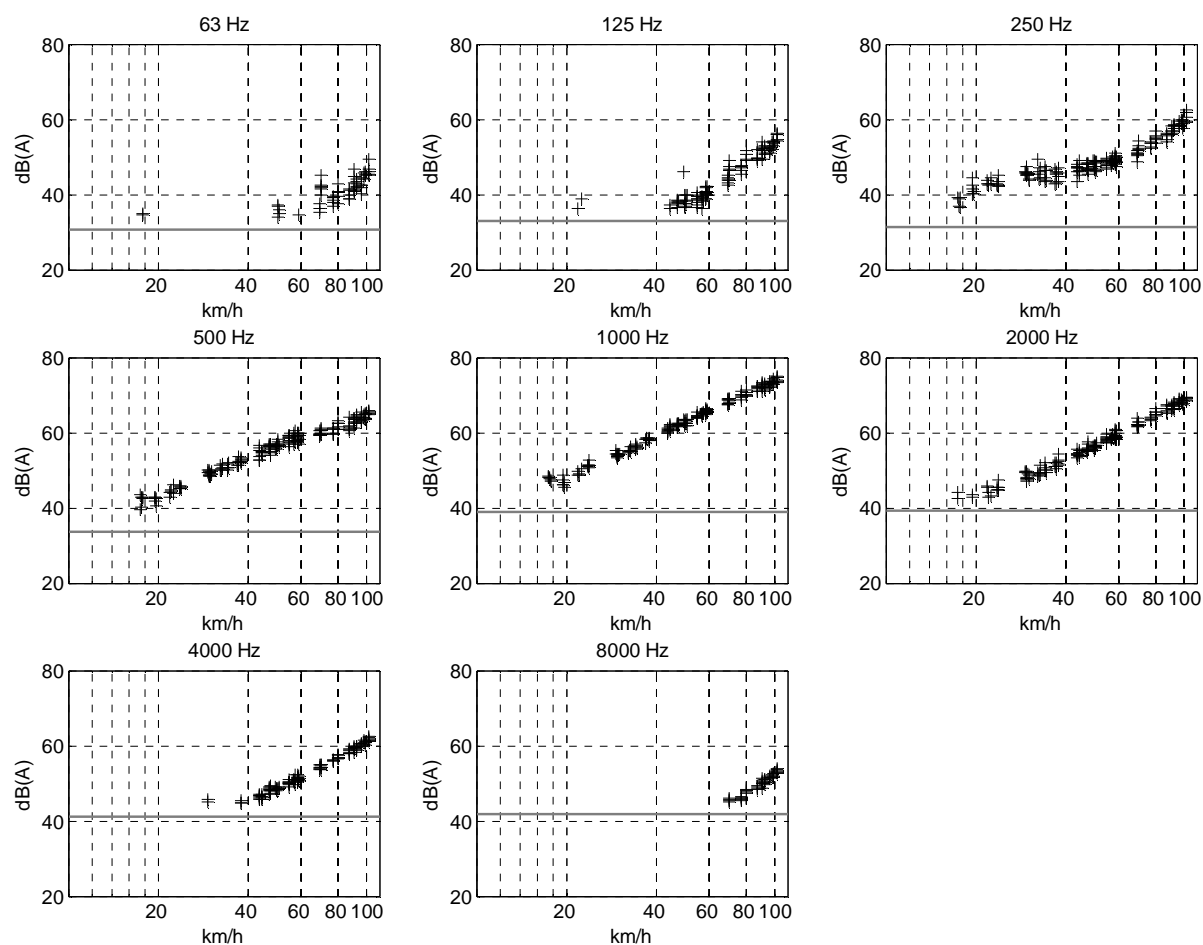


Figure 25: Distribution of the maximum sound pressure level in dB(A) in octave bands for the Citroen C-Zero at constant speed, at 7.5 m from the track centre

For the drive-by tests (under acceleration), either the stationary vehicle started 10 metres before the first microphone or it arrived at constant speed and began to accelerate 10 metres before the same waypoint. Two acceleration types were tested: moderate or full acceleration. Moderate acceleration<sup>14</sup> corresponds to an intermediate stroke of the driver's accelerator. Due to high acceleration rate under full throttle<sup>15</sup>, measures are available from 30 km/h only. In both acceleration cases, the acceleration rate decreases as the initial speed is larger. Figure 26 shows the A-weighted maximum global noise levels at the vehicle pass-by, as a function of the instantaneous speed recorded in front of the microphone. Global noise still increases linearly with  $\log(\text{speed})$ . The figures representing the noise distribution in octave bands are given in Appendix A (Figure A1 and Figure A2). A strong acceleration significantly increases the emitted noise in the frequency bands over 500 Hz.

<sup>14</sup> Moderate acceleration: approximately from  $0.7 \text{ m/s}^2$  at the highest speeds to  $2.3 \text{ m/s}^2$  at the lowest speeds of the test (average acceleration rate over a length of 20 m).

<sup>15</sup> Full acceleration: approximately from  $0.7 \text{ m/s}^2$  at the highest speeds to  $2.9 \text{ m/s}^2$  at the lowest speeds of the test (average acceleration rate over a length of 20 m).

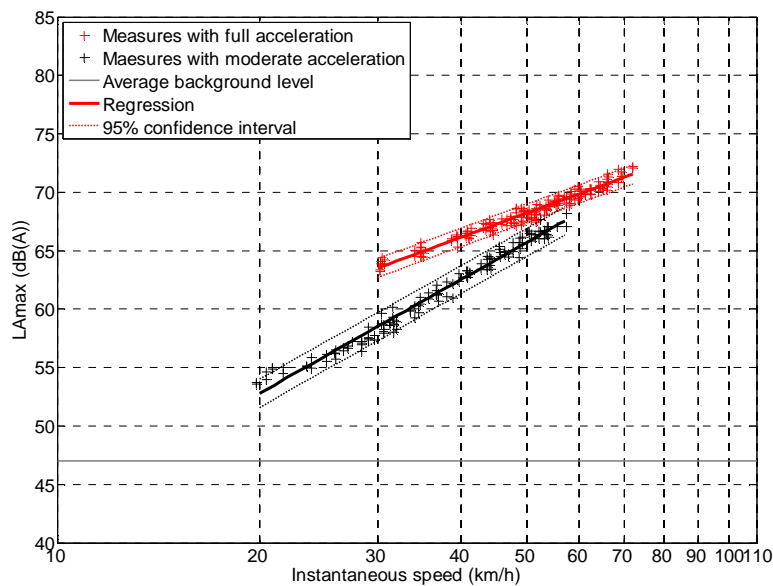


Figure 26 : Global A-weighted maximum sound pressure level of the C-Zero under moderate acceleration (black) and full acceleration (red) at 7.5 m from the track centre, as a function of the instantaneous speed in front of the microphone

Two conditions were tested with the vehicle slowing down. “Deceleration” concerns the case where the accelerator pedal is released without using the brake pedal: this operating condition already activates the kinetic energy recovery system (KERS) for recharging the batteries. In the second test, the brake pedal is used as well; the motor load increases for recovering kinetic energy. Under deceleration<sup>16</sup> (resp. braking<sup>17</sup>), the vehicle arrived at various constant speeds and the acceleration pedal was released (resp. the brake pedal was depressed) 10 metres before the test area. Braking definitely increases the emitted noise (Figure 27), which is clearly audible on the trackside, but the respective contribution of the brakes and the KERS cannot be separated from the microphone measurement. The noise distribution in octave bands can be seen in the Appendix A (Figure A3 and Figure A4). Braking increases noise in all frequency bands below 30-40 km/h.

<sup>16</sup> Deceleration: approximately from  $-1.2 \text{ m/s}^2$  at the highest speeds to  $-0.3 \text{ m/s}^2$  at the lowest speeds of the test (average deceleration rate over a length of 20 m).

<sup>17</sup> Braking: approximately from  $-3.4 \text{ m/s}^2$  at the highest speeds to  $-1.5 \text{ m/s}^2$  at the lowest speeds of the test (average deceleration rate over a length of 20 m).



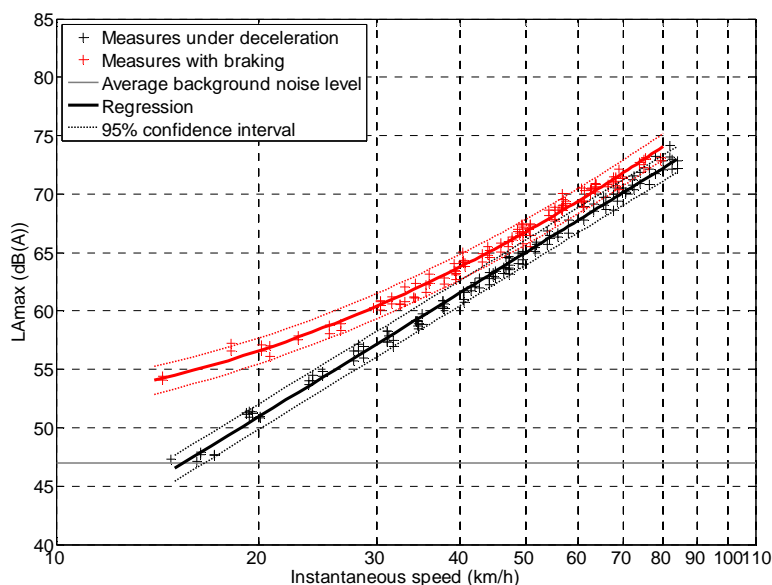


Figure 27: Global A-weighted maximum sound pressure level of the C-Zero under deceleration (black) and braking (red) at 7.5 m from the track centre, as a function of the instantaneous speed in front of the microphone

Finally, when comparing all the operating conditions to steady speed, it can be noticed that deceleration does not modify the global noise level, moderate acceleration increases it only slightly, whereas braking and above all a strong acceleration rise noise levels significantly (Figure 28). The braking operation has an effect over the whole speed range. Noise variations with respect to steady speed are given in Table 4 for some noteworthy low speed values.

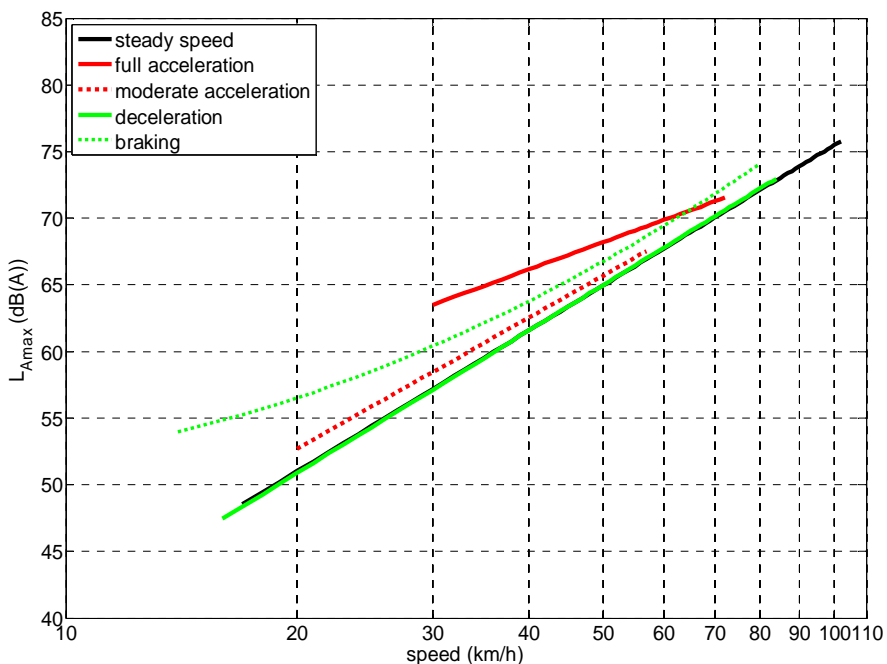


Figure 28: Comparison of the global A-weighted maximum sound pressure level emitted by the C-Zero in all operating conditions, at 7.5 m from the track centre

Table 4: Noise variation in different running conditions compared with pass-bys at constant speed of the Citroen C-Zero, at 7.5 m from the track centre

Reference: Steady speed	Instantaneous speed		
	20 km/h	30 km/h	50 km/h
Moderate acceleration	+1.7 dB(A)	+1.3 dB(A)	+0.7 dB(A)
Full acceleration		+6.3 dB(A)	+3.2 dB(A)
Deceleration	-0.2 dB(A)	-0.1 dB(A)	0 dB(A)
Braking	+5.5 dB(A)	+3.2 dB(A)	+1.8 dB(A)

The European project City Hush performed measurement on a Citroen C-Zero, a Peugeot iOn and a Mitsubishi iMiev, which actually derive from the same car model, on a test track with a dense bitumen asphalt surface with maximum stone size 8 mm (cf subsection 3.2). The speed ranged from 15 to 50 km/h for the constant speed tests. In this case the noise levels given in CityHush are approximately 5 dB(A) lower than those of FOREVER. Differences may provide from the road surfaces, since the one used in CityHush seems quite smoother. However, the granulometry difference is not sufficient to explain such a difference, and resorting to texture spectra could be a way to deepen this issue.

The noise level values under acceleration in CityHush are given as a function of the initial speed at the entrance of the test area. From our tests with a start speed of 20 km/h, the instantaneous speed is about 35 km/h at the microphone position 10 metres further with a full acceleration, it becomes 44 km/h (resp. 58 km/h) for a start speed of 30 km/h (resp. 50 km/h). Thus, the CityHush results need to be shifted towards higher speed to be compared with FOREVER. On the same speed scale, the full acceleration tests in CityHush give noise levels from 64 dB(A) to 67 dB(A), increasing with a slow velocity slope for each of the three vehicles tested, whereas the C-Zero noise levels in FOREVER rise from 65 to 69 dB(A). The difference between both experiments is lower than at constant speed, probably due to the major contribution of propulsion noise in this operating condition, thus reducing the relative influence of the road surface. In octave bands, we confirm that the velocity slope is smaller than at constant speed but with a higher rate than in CityHush nonetheless.

#### 4.1.3 Noise emission of a large family hybrid passenger car

The noise emission of a 'large family'<sup>18</sup> passenger car with a parallel hybrid electric powertrain has been investigated. The engine powertrain is equipped with an automatic 6-speed gearbox. Among the different operating modes available for the driver, the vehicle was tested in the following modes: the all-electric mode with the vehicle powered by the sole electric motor, as well as two hybrid modes (named here Hybrid1 and Hybrid2) with the simultaneous working of the engine and the motor. The results with a hybrid mode selection but for which the engine occurred to switch off at low speed have been grouped within the all-electric mode. The vehicle is equipped with tyres out of a sport-oriented range. Both acoustic measurement devices presented in subsection 4.1.1 have been used to describe the noise emission of this hybrid vehicle.

<sup>18</sup> According to the classification EuroNCAP ([www.euroncap.com](http://www.euroncap.com))

#### 4.1.3.1 Noise levels at 7.5 m

The measurement at constant speed was made in various speed ranges according to the operating mode: from 17 to 45 km/h in electric mode, from 15 to 114 km/h for both hybrid modes altogether. When the engine is working, the emitted noise depends on the engine speed and the gear selection. Thus, when represented as a function of vehicle speed, the noise level points out discontinuities at the speed values where the gear is shifted, as it can be seen on Figure 29. The gear shifts are acoustically noticeable only up to 40 km/h (gear ratio 4) on the global levels and still up to 60 km/h (gear ratio 5) in some octave bands where propulsion noise is significant (see Appendix B, Figure B5). In hybrid mode, the emitted noise results from the contribution of a propulsion noise component, depending on  $\log(\text{engine speed})$  and a rolling noise component which linearly depends on  $\log(\text{speed})$ . In the electric mode, the noise level increase is clearly linear with  $\log(\text{speed})$ , both in global levels and in octave bands, over the available speed range; the global A-weighted maximum sound pressure level at 7.5 m is given by:

$$L_{A\max} = 75.1 + 38.9 \log\left(\frac{v}{70}\right) \text{ dB(A)} \quad (32)$$

where  $v$  is the vehicle speed within the range [17-45] km/h. Thus, a doubling of the vehicle speed increases the maximum pass-by noise level by 11.7 dB(A) in electric mode.

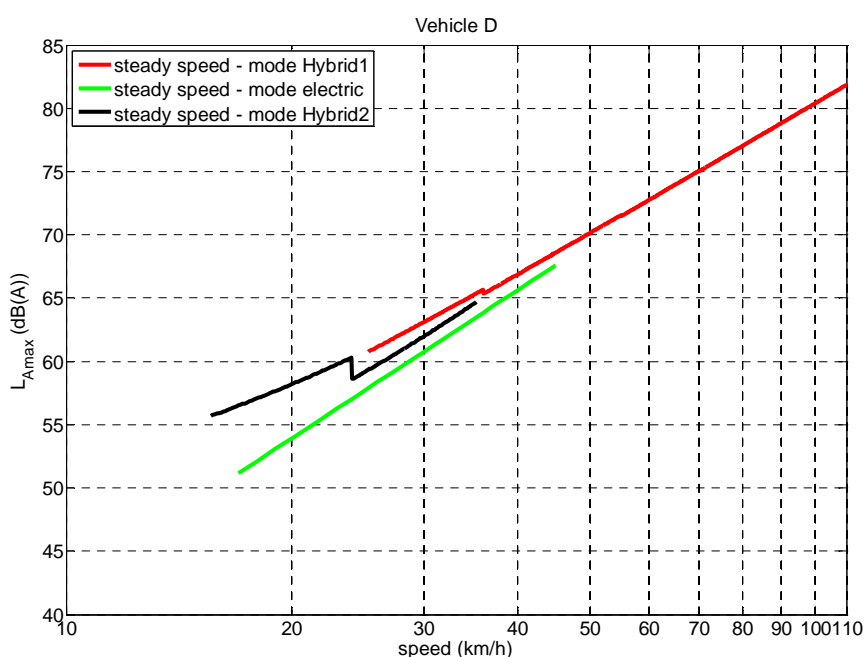


Figure 29: Global A-weighted maximum sound pressure level of the hybrid passenger car at constant speed at 7.5 m from the track centre, in electric mode (green), in mode Hybrid1 (red) and Hybrid2 (black)

The measurement protocol for the accelerating / decelerating / braking vehicle is similar with the one previously described for the C-Zero.

In acceleration whatever the initial speed, the engine switched on and the vehicle was in hybrid mode during the measurement. The instantaneous engine speed and gear ratios were not available under acceleration; the only usable parameter is the vehicle speed. Full

acceleration resulted in high acceleration rates<sup>19</sup> with this quite powerful car, with potentially high engine speeds, not much representative of a usual driving style and is not reported here; the corresponding maximum noise levels gave non-repetitive, widely spread values. Moderate acceleration corresponds to an intermediate stroke of the driver's accelerator<sup>20</sup>. With a moderate acceleration, the overall noise trend is linear with  $\log(\text{speed})$ , as it can be seen in Figure 30. The spread of the individual values may be significant in some octave bands, probably linked to the propulsion noise contribution (not illustrated).

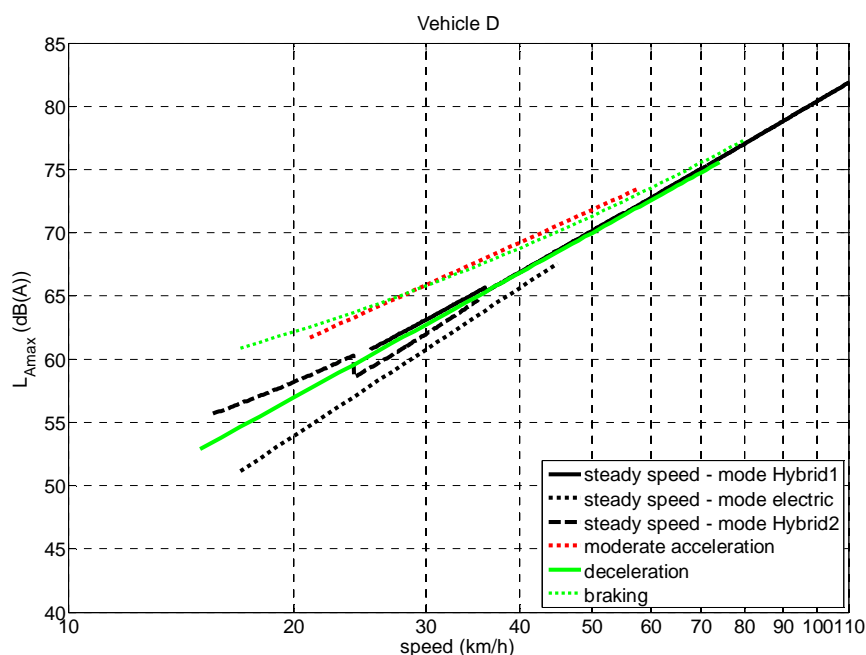


Figure 30: Comparison of the global A-weighted maximum sound pressure level emitted by the hybrid passenger car in all operating conditions, at 7.5 m from the track centre

For the deceleration<sup>21</sup> and braking<sup>22</sup> tests, the initial speed<sup>21</sup> ranged from 50 to 90 km/h; thus the vehicle was systematically arriving in hybrid mode. It generally switched to the electric mode when the instantaneous speed fell below 50 km/h. When in hybrid mode on the decelerating (resp. braking) test area, the engine speed turned out to be low. In both cases the energy recovery system was activated. The impact of the powertrain operating mode is noticeable neither on the global noise levels nor in octave bands. Over the instantaneous speed range tested, deceleration provided noise levels similar to pass-bys at constant speed in hybrid mode, whereas braking involved noise levels analogous to moderate acceleration. Table 5 compares the global noise levels in the various operating conditions, relatively to pass-bys at constant speed in hybrid mode. At speeds where two hybrid modes were available, the reference is the noisiest one.

<sup>19</sup> Full acceleration: approximately from  $0.9 \text{ m/s}^2$  at the highest speeds to  $2.6 \text{ m/s}^2$  at the lowest speeds of the test (average acceleration rate over a length of 20 m).

<sup>20</sup> Moderate acceleration: approximately from  $0.6 \text{ m/s}^2$  at the highest speeds to  $1.9 \text{ m/s}^2$  at the lowest speeds of the test (average acceleration rate over a length of 20 m).

<sup>21</sup> Deceleration: approximately from  $-1.1 \text{ m/s}^2$  at the highest speeds to  $-0.7 \text{ m/s}^2$  at the lowest speeds of the test (average deceleration rate over a length of 20 m).

<sup>22</sup> Braking: approximately from  $-3.4 \text{ m/s}^2$  at the highest speeds to  $-1.9 \text{ m/s}^2$  at the lowest speeds of the test (average deceleration rate over a length of 20 m).

Table 5: Noise variation in different conditions compared with pass-bys at constant speed of the hybrid passenger car in hybrid mode (max. level of Hybrid1 and Hybrid2), at 7.5 m from the track centre

Reference: hybrid mode at constant speed	Vehicle speed			
	20 km/h	30 km/h	40 km/h	50 km/h
Electric mode at constant speed	-4.3 dB(A)	-2.3 dB(A)	-1.2 dB(A)	
Moderate acceleration		+2.8 dB(A)	+2.7 dB(A)	+1.7 dB(A)
Deceleration	-1.2 dB(A)	-0.4 dB(A)	0 dB(A)	-0.2 dB(A)
Braking	+4.0 dB(A)	+2.7 dB(A)	+1.9 dB(A)	+1.2 dB(A)

#### 4.1.3.2 Analysis of the noise sources

The microphone array provides information on the noise sources and their behaviour depending on the operating conditions.

At constant speed the noise source distribution on the hybrid vehicle depends on the operating mode of the powertrain, particularly at low speed. Since the engine is located near the front axle and the electric motor near the rear axle, the respective noise contribution of both powering units can be identified, although rolling noise differences due to some tyre wear discrepancy cannot be dismissed.

Pass-bys at low steady speed in all-electric mode show a noise emission level slightly higher by 1-2 dB(A) around the rear axle (rolling noise + electric motor noise) than near the front axle (rolling noise only), as observed in Figure 31 (left). In the hybrid operating modes, the noise emission increases significantly due to the working engine located near to the front axle (Figure 31, right).

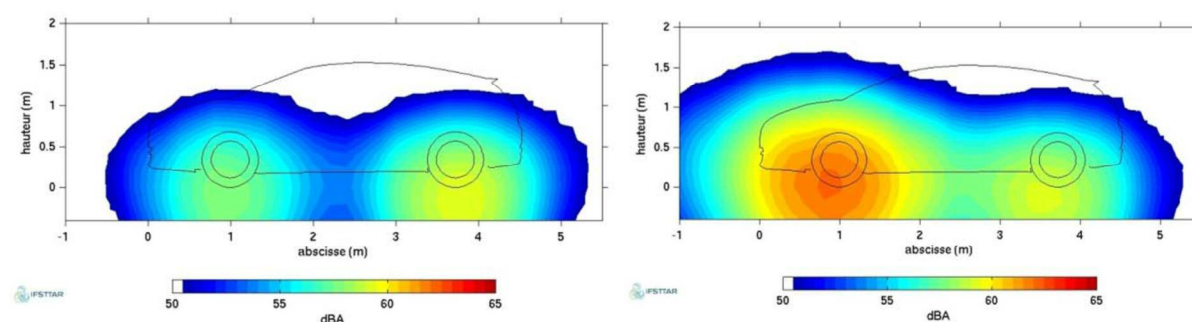


Figure 31: Noise maps of the hybrid car at steady speed 23 km/h in electric mode (*left*) and in hybrid mode (*right*) – Global sound pressure levels in dB(A) at the reference distance 2.7 m from the vehicle side

In the electric mode (up to 55 km/h), the noise level values measured by the array on each wheel area increase linearly on a  $\log(\text{speed})$  scale (Figure 32). On the front wheel area in hybrid mode, the additional noise brought by the engine is noticeable up to 40 km/h but the influence of the engine speed and gear shifts cannot be detected (Figure 32, left), contrary to the standard measurement presented in subsection 4.1.3.1. The representation of the global

noise contribution of the engine power unit by a constant level with speed is a valuable approximation, at least up to the 6<sup>th</sup> gear ratio shifting (i.e. 80 km/h). It can be checked that the rolling noise component estimated on the front source zone in hybrid mode coincides with the measures in electric mode (where rolling noise is the only noise source on this vehicle area). Figure 33 groups the average trends observed on both axle areas. With the assumption that rolling noise is identical on both axles, the noise difference between front and rear axle in electric mode could be ascribed to the contribution of the electric power unit.

In frequency<sup>23</sup>, sound level differences between hybrid and electric modes occur below 30 km/h in the octave bands up to 1000 Hz and below 40 km/h in the 2000 Hz and 4000 Hz octave bands (Appendix B, Figure B7). As it could be expected, the powertrain mode does not affect the noise emission from the rear axle area, since the electric motor was running during almost all pass-bys (Appendix B, Figure B8).

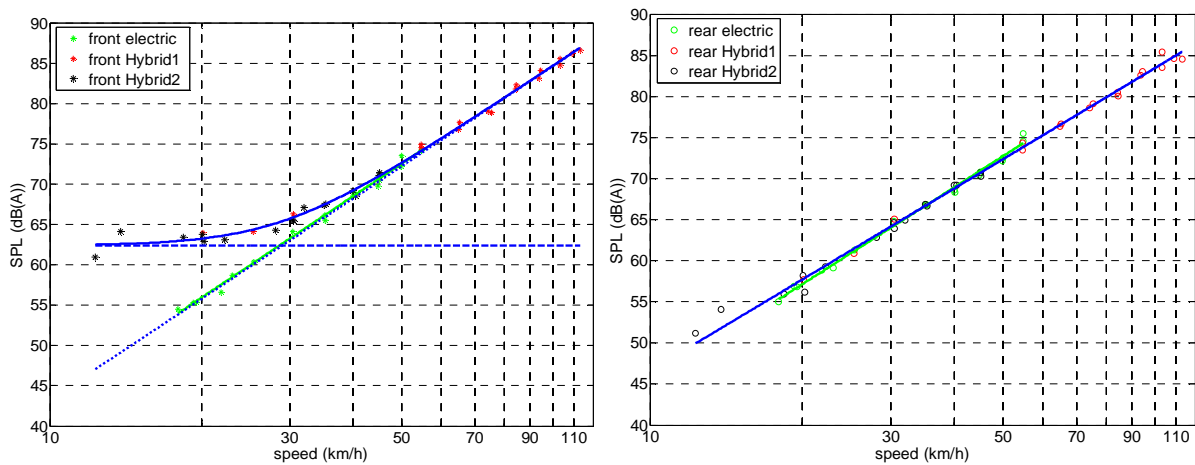


Figure 32: Noise contribution of the front axle area (*left*) and the rear axle area (*right*) of the HEV at constant speed – Global sound pressure levels in dB(A) at the reference distance 2.7 m

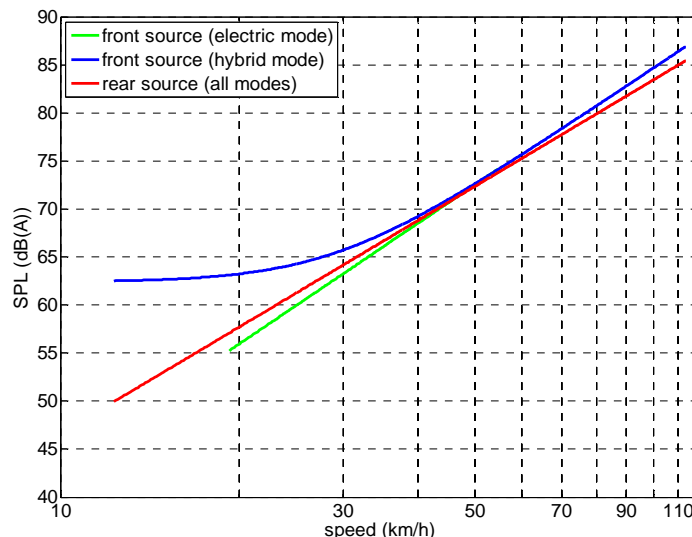


Figure 33: Comparison of the average contribution of the front axle area and the rear axle area of the HEV at constant speed, in the electric and hybrid modes – Global sound pressure levels in dB(A) at the reference distance 2.7 m

<sup>23</sup> Due to the poor array performance at low frequency, the results provided in the octave band 63 Hz should be considered with cautious reliance only.

Finally, Figure 34 and Figure 35 illustrate respectively the noise contribution of the engine on the accelerating vehicle in hybrid mode and of the rear axle area on the braking vehicle, at 30 km/h in both cases. In the latter case, the energy recovery is active.

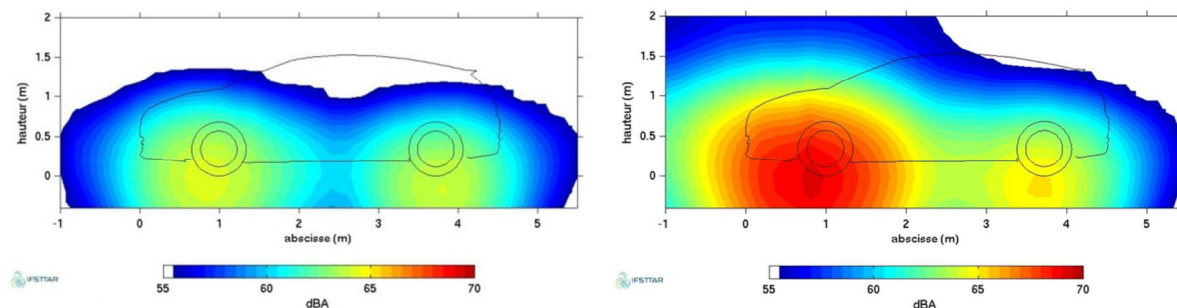


Figure 34: Noise maps of the hybrid car at 30 km/h (in front of the array) in hybrid mode, at steady speed (*left*) and in acceleration (*right*) – Global sound pressure levels in dB(A) at the reference distance 2.7 m

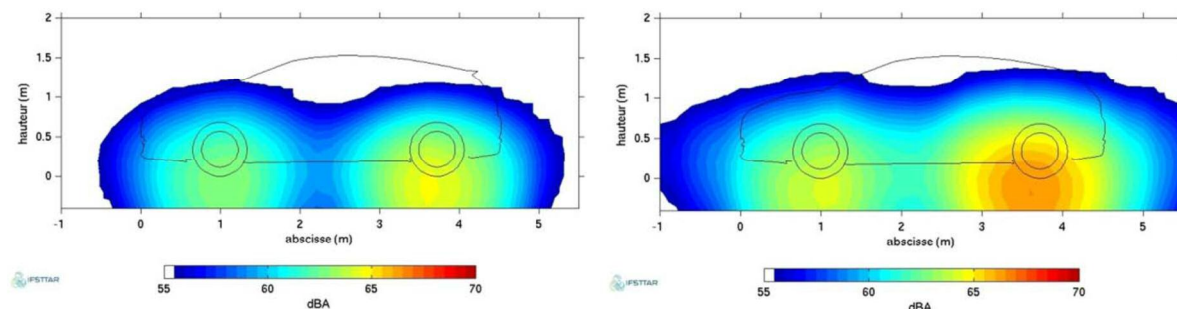


Figure 35: Noise maps of the hybrid car at 30 km/h (in front of the array) in electric mode, at steady speed (*left*) and under braking (*right*) – Global sound pressure levels in dB(A) at the reference distance 2.7 m

#### 4.1.4 Noise emission of an electric truck

The noise emission of an electric truck from category N2 has been measured. In the CNOSSOS-EU classification, it belongs to category 2 (medium heavy vehicles), characterized by a gross vehicle weight greater than 3.5 tons, two axles and twin tyres on the rear axle. Its maximum speed is 90 km/h. It is fitted with a 6-speed automatic gearbox. The tyres mounted on this vehicle correspond to a range intended for utility vehicles and vans.

For confidentiality reasons, only the results given by the set of microphones at the standard position 7.5 m from the track centre are reported here. The vehicle was unloaded during the measurement. The operating conditions which have been investigated are: constant speed, full acceleration and deceleration. Since the deceleration rate is large when releasing the accelerator pedal for a maximum efficiency of kinetic energy recovery, the use of the braking pedal is in practice almost limited to emergency braking events and has not been tested acoustically.

Pass-bys at constant speed were conducted from 12 to 75 km/h. The acoustical influence of the selected gear is very small comparatively to the measures spreading and is not taken into account in the analysis below. The global A-weighted maximum sound pressure level follows a quasi-linear trend with  $\log(\text{speed})$ , given by (Figure 36):

$$L_{A_{\max}} = 75.5 + 30.6 \log\left(\frac{v}{70}\right) \text{ dB(A)} \quad (33)$$

where  $v$  is the vehicle speed in km/h. Doubling the speed increases noise by 9.2 dB(A).

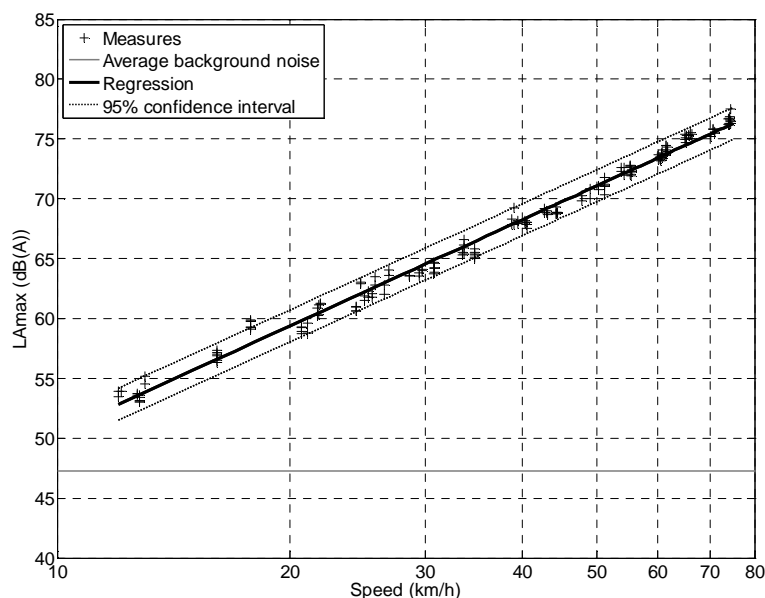


Figure 36: Global A-weighted maximum sound pressure level of the electric truck (cat. N2) at constant speed at 7.5 m from the track centre

In frequency, the vehicle noise was low comparatively to background noise in the octaves 63 Hz, 125 Hz and 4000 Hz. Consequently, some results have been removed below 40 km/h (Appendix C, Figure C9). However, the remaining values lead us to suspect that the noise level behaviour differs from a linear trend in these frequency bands.

When the truck was accelerating<sup>24</sup> (Figure 37, left), all pass-bys occurred with the same gear over the test speed range. The global noise trend exhibits an irregular evolution around an average trend of  $20.4 \log(v/70)$ . However in frequency, the noise level remains almost constant in some octave bands and even decreases in the octave 8000 Hz when speed increases (Appendix C, Figure C10).

<sup>24</sup> Acceleration rate: approximately from  $0.5 \text{ m/s}^2$  at the highest speeds to  $1.1 \text{ m/s}^2$  at the lowest speeds of the test (mean acceleration rate over a length of 20 m).



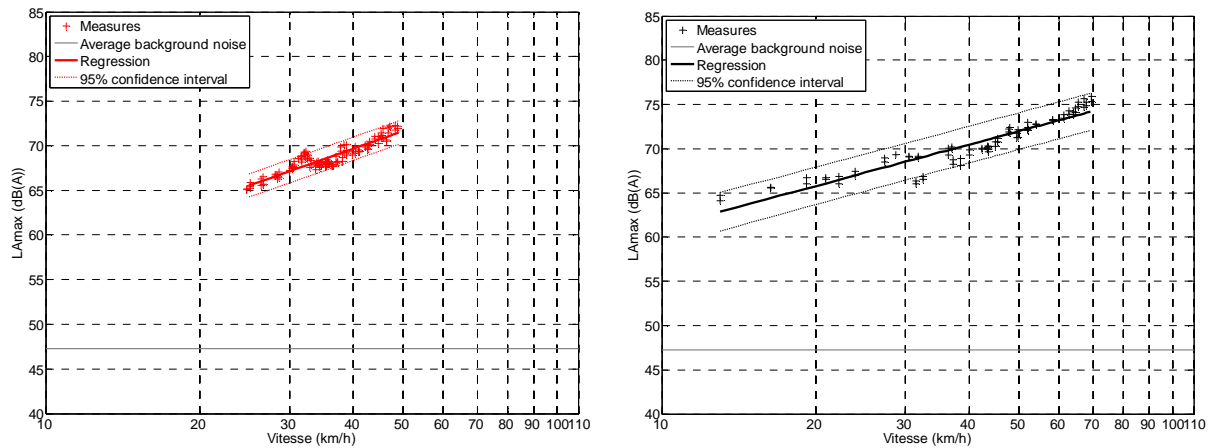


Figure 37: Global A-weighted maximum sound pressure level of the electric truck (cat. N2) under acceleration (*left*) or deceleration (*right*), at 7.5 m from the track centre

Finally, the role of the selected gear is more perceptible under deceleration<sup>25</sup> (Figure 37, right). For instance, a gear shift occurred between 30 and 40 km/h, also detectable in several octave bands (Appendix C, Figure C11). As a first approximation, it is represented here by a regression linearly depending of  $\log(\text{speed})$ . On average, the decelerating vehicle happens to be slightly noisier than when accelerating (Figure 38 and

Table 6).

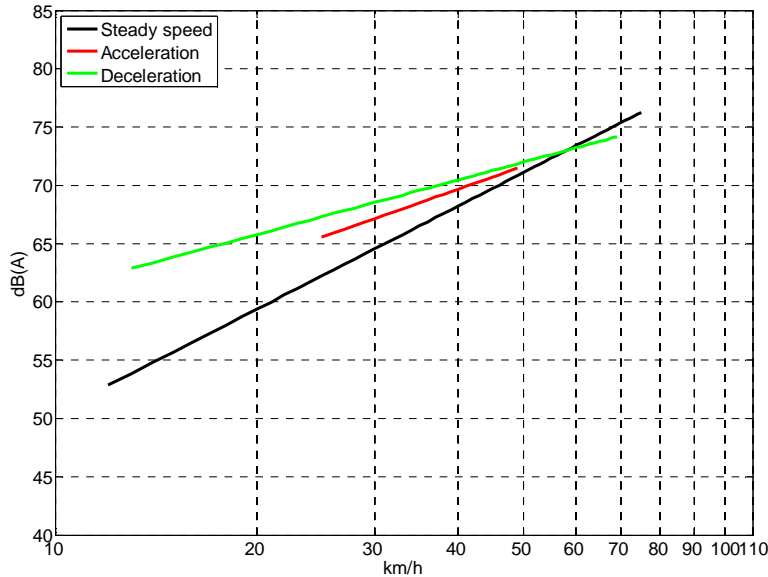


Figure 38: Comparison of the global A-weighted maximum sound pressure level emitted by the electric truck in all operating conditions, at 7.5 m from the track centre

<sup>25</sup> Deceleration: approximately from  $-2.2 \text{ m/s}^2$  at the highest speeds to  $-1.3 \text{ m/s}^2$  at the lowest speeds of the test (average deceleration rate over a length of 20 m).



Table 6: Noise variation in different running conditions compared with pass-bys at steady speed of the electric truck, at 7.5 m from the track centre

Reference: Steady speed	Vehicle speed			
	20 km/h	30 km/h	40 km/h	50 km/h
Full acceleration		+2.6 dB(A)	+1.5 dB(A)	
Deceleration	+6.4 dB(A)	+4.0 dB(A)	+2.2 dB(A)	+0.9 dB(A)

#### 4.1.5 Main findings from the experiment with EVs and HEVs

An experiment on the noise emission of three vehicles has been undertaken on a test track with a dense asphalt concrete 0/10 road surface. The vehicles are: a small electric passenger car, a large hybrid passenger car and an electric truck. They have been tested at steady speed, under moderate or full acceleration, under deceleration or braking.

##### Concerning the background noise:

Background noise level may become problematic for measuring quiet vehicles at low speed, in global levels and even more in a frequency analysis. The lowest frequencies (octaves 63 Hz and 125 Hz) and the highest frequencies (octave 8000 Hz) are more critically concerned for road vehicles, depending on background noise spectra.

##### Concerning the separation of propulsion noise and rolling noise:

The EVs and HEVs generally use either a direct transmission or an automated gearbox and the transmission cannot be disengaged. Thus, coast-by measurement condition cannot be used.

For vehicles equipped with a gearbox, the knowledge of the engine/motor speed in addition to the vehicle speed provides two independent parameters, generally helping to separate propulsion noise from rolling noise. Despite the presence of a gearbox on the electric truck, differences in the motor speed were hardly detectable on the measured noise levels in some driving conditions, preventing us from implementing a meaningful noise component separation.

For vehicles with a direct transmission, vehicle speed is the only parameter steering the two noise components (propulsion noise and rolling noise). They cannot be separated from common pass-by noise measurement without complementary information.

The use of indoor test condition and/or simultaneous on-board instrumentation should help to focus on the propulsion noise component.

##### Concerning the noise emitted by electric vehicles:

At steady speed the global A-weighted noise pressure level measured at vehicle pass-by increases linearly with  $\log(\text{speed})$ . This linear trend also occurs in the middle frequency range, where rolling noise is well-known to have a significant contribution. These middle frequency bands are dominating over most of the speed range. The trend is non-linear at low and high frequencies.

Acceleration obviously increases the emitted noise. For a given acceleration condition (moderate or full acceleration), the noise increase slope with respect to the instantaneous pass-by speed is smaller than at steady speed; it may even decrease in the octave 8000 Hz. A deceleration (without braking) does not change much the emitted noise if the deceleration rate is moderate, but the noise was observed to increase significantly if the energy recovery was strong, with or without braking.

### Concerning the noise emitted by the hybrid vehicle:

The comments on the electric vehicles also apply to the hybrid vehicle in electric mode. In electric mode at low speed, the noise contribution from the rear axle (propulsion noise + rolling noise) is 1-2 dB(A) higher than the one from the front axle (rolling noise only).

At 20 km/h, the hybrid vehicle in electric mode is about 4 dB(A) quieter than in hybrid mode. At steady speed, global noise emission differences between the electric and the hybrid mode occur up to 40 km/h. There is no difference over 40 km/h. In frequency, this speed bound varies from 30 to 40 km/h, depending on the octave band.

When decelerating (without braking), the global noise emission is similar to pass-bys at steady speed in hybrid mode.

The noise level is similar in moderate acceleration and in braking situation.

## 4.2 Analysis of data collection available by FOREVER partners

In order to set out an appraisal on the noise emission of EVs and HEVs, appropriate data available by the project partners have been collected. The three vehicles tested in the previous section have been included. The data collection is listed in the next tables by vehicle categories, in accordance with the classification used in the CNOSSOS-EU method.

Table 7: Description of the EVs and HEVs dataset available from the project partners, for light vehicles (CNOSSOS cat. 1) measured at steady speed, at 7.5 m from the track centre (blue = TRL data; black = IFSTTAR data)

EC vehicle category	Vehicle	Powertrain mode	Road surface <sup>26</sup>	Dataset	
				Global SPL	Octave SPL
L6 <sup>27</sup>		Electric	14mm SMA	✓	✓
M1	Small	Electric	14mm SMA	✓	✓
M1	Medium	Series-parallel Hybrid	14mm SMA	✓	✓
N1	Full-size van	Electric	14mm SMA	✓	✓
M1	Small	Electric	DAC 0/10	✓	
M1	Small	Electric	DAC 0/10	✓	✓
M1	Medium	Series-parallel Hybrid	DAC 0/10	✓	
		Electric		✓	
M1	Small	Electric	DAC 0/10	✓	✓
M1	Medium	Parallel hybrid	DAC 0/10	✓	✓
		Electric		✓	✓

<sup>26</sup> SMA=Stone Mastic Asphalt; DAC=Dense Asphalt Concrete

<sup>27</sup> This dataset has been included here, although theoretically within category 4b of CNOSSOS-EU.

Table 8: Description of the EVs and HEVs dataset available from the project partners for medium heavy vehicles (CNOSSOS cat. 2) measured at steady speed, at 7.5 m from the track centre (IFSTTAR data)

EC vehicle category	Powertrain mode	Road surface <sup>26</sup>	Dataset	
			Global SPL	Octave SPL
N3	Parallel Hybrid	DAC 0/10	✓	✓
	Electric	DAC 0/10	✓	✓
M3	Series Hybrid	DAC 0/10	✓	✓
	Electric	DAC 0/10	✓	✓
N2	Electric	DAC 0/10	✓	✓

Only measures at steady speed providing noise levels at 7.5 m from the track centre are considered here. Figures gathering the acoustical behaviour of the vehicles are presented and commented below, by vehicle category, and compared with the sound emission model provided in CNOSSOS-EU for conventional vehicles with an internal combustion engine (ICE).

#### 4.2.1 EVs and HEVs from Category 1

The collection of data includes three electric vehicles, measured from approximately 20 to 50 km/h by TRL on a SMA 0/14 road surface and three electric vehicles from 16 to 102 km/h at most measured by IFSTTAR on a DAC 0/10. Two IFSTTAR hybrid vehicles measured in electric mode between 12 to 45 km/h are also included. A-weighted maximum sound pressure levels, at steady speed and at 7.5 m from the track centre, are considered here.

On average, the TRL vehicles happen to be noisier than those measured by IFSTTAR (Figure 39). Since the number of vehicles is small, no definite conclusions can be drawn. Beyond vehicle discrepancies, road roughness and surface type differences may play a significant role. At any speed between 20 and 50 km/h, the gap from the quietest to the noisiest vehicle is 4.5 dB(A).

CNOSSOS-EU, providing a model for the noise emission from ICE vehicles, clearly overestimates the global noise emission from the set of electric vehicles, either through the propulsion noise component at low speed or through the rolling noise component. No correction has been used here for road surfaces differing from the reference conditions. Since CNOSSOS-EU is actually specified in octave bands from 63 Hz up to 8000 Hz, it is particularly interesting to compare the EV dataset to CNOSSOS-EU in frequency. For each vehicle, the noise evolution with speed has been approximated either by a linear or a quadratic regression in each frequency band (Figure 40). We can notice that the global noise predominance of the TRL vehicles comes primarily from the octaves 500 Hz and 1000 Hz. Finally, CNOSSOS-EU appears to be inappropriate for the measured EVs in all frequency bands, for the propulsion noise component at low speed. This is the subject of section 0, which proposes a model for electric vehicles.

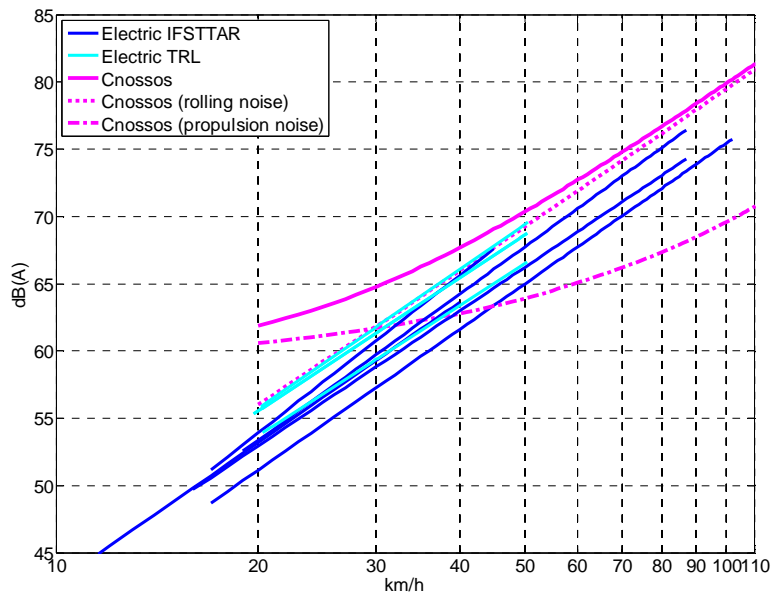


Figure 39: Data set of global noise measurement on electric vehicles at steady speed and CNOSSOS-EU model in reference conditions at 7.5 m from the track centre (Category 1)

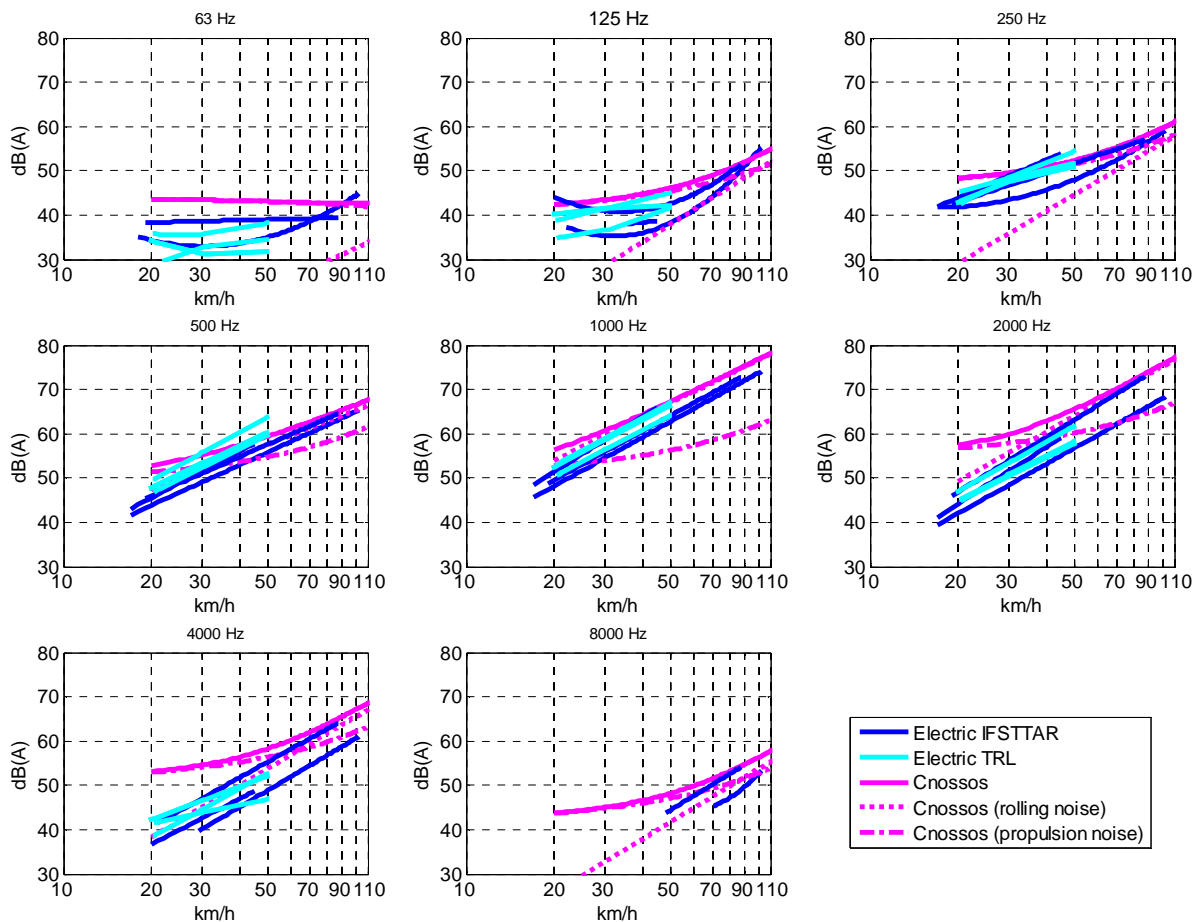


Figure 40: Data set of noise measurement on electric vehicles at steady speed and CNOSSOS-EU model in octave bands in reference conditions, at 7.5 m from the track centre (Category 1)

Hybrid vehicles are now analysed. Comments on this vehicle category should be considered as an initial indication, since the sample size is small with only three vehicles. At high speed, one vehicle has a different trend from the others, which may be due to different tyre specifications (Figure 41). Otherwise, CNOSSOS-EU overestimates the global noise at low speed, mainly caused by the propulsion noise component, whereas it appears to be appropriate at high speed where the model is ruled by rolling noise.

In frequency, the main discrepancies between the hybrid vehicles and CNOSSOS-EU occur at high frequency above the octave 2000 Hz, with a strongly overestimated propulsion noise component (Figure 42).

As a conclusion, there is evidence that CNOSSOS-EU does not correctly predict the set of electric and hybrid vehicles measured by TRL and IFSTTAR, with more or less discrepancy depending on vehicle and frequency. An overestimation of the propulsion noise component is recurrent in most cases. However, before attempting to propose any CNOSSOS modification for these vehicle categories, it would be advisable to first check CNOSSOS-EU adequacy to ICE vehicle noise emission on the same test sites. This is addressed in section 0.

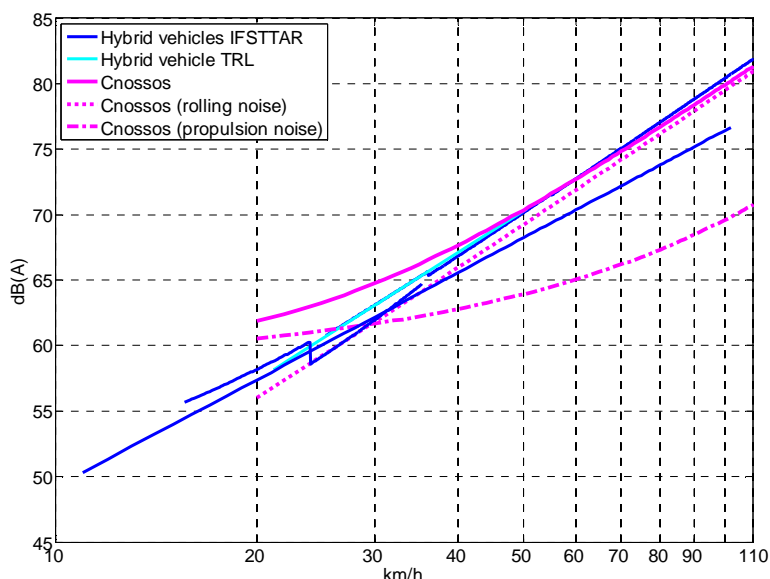


Figure 41: Data set of global noise measurement on hybrid vehicles at steady speed and CNOSSOS-EU model in reference conditions, at 7.5 m from the track centre (Category 1)

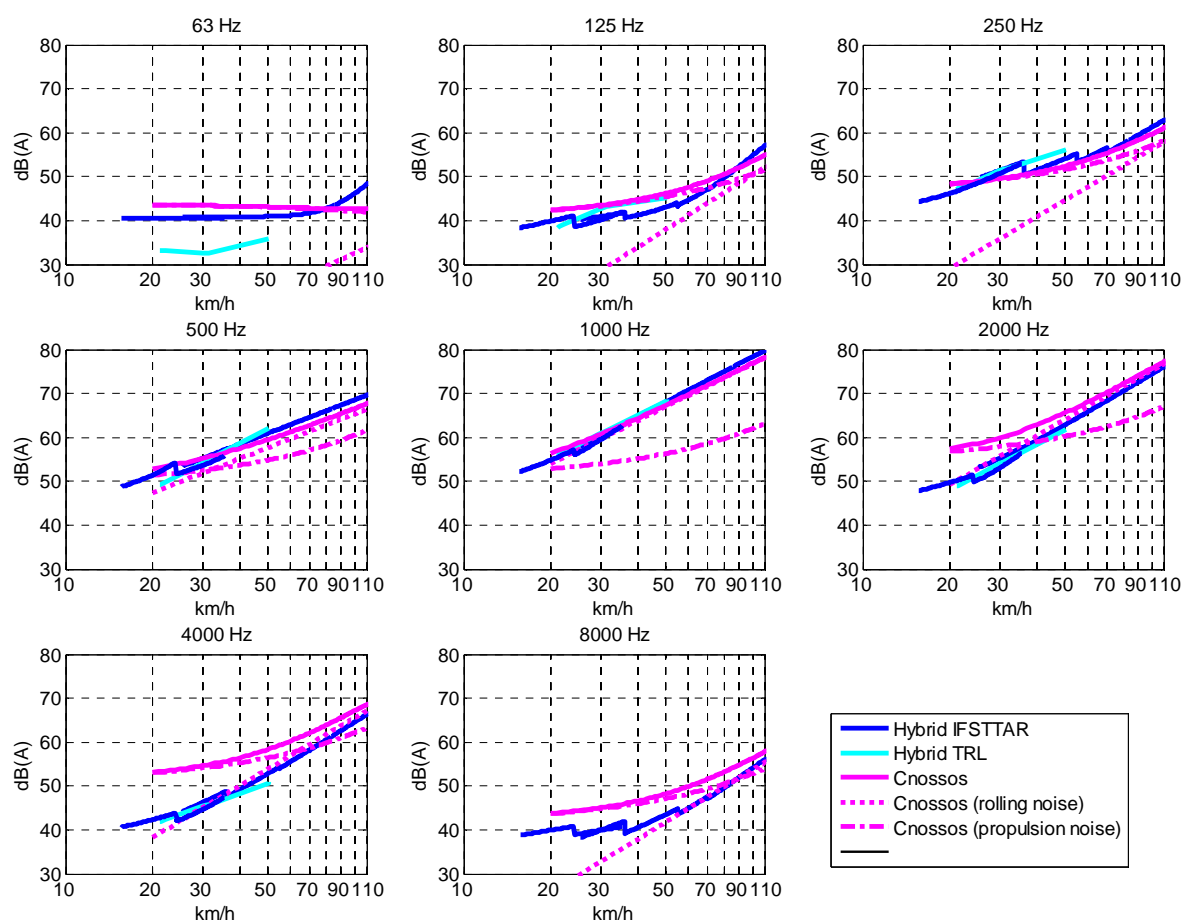


Figure 42: Data set of noise measurement on hybrid vehicles at steady speed and CNOSSOS-EU model in octave bands in reference conditions, at 7.5 m from the track centre (Category 1)

## 4.2.2 EVs and HEVs from Category 2

Category 2 concerns medium heavy vehicles, with a gross vehicle weight (GVW) larger than 3.5 tons, two axles and twin wheels on the rear axle. Data from only three vehicles are available in this category: two hybrid and one electric vehicle, all measured on the IFSTTAR test site with a DAC 0/10 road surface. Both hybrid ones can also be operated in all-electric mode. When differences occur with the vehicle side, measurement results of both sides are displayed. *Due to the small number of vehicles, the observed tendency is only indicative and should be completed by a larger vehicle set.* The presence of a broken line renders perceptible noise variations at gear shifting if the vehicle is equipped with a gearbox.

Even if belonging to the same CNOSSOS-EU category, the electric and the hybrid vehicles which have been tested differ much by their GVW and their tyre size. During the measurement, the hybrid vehicles were loaded in accordance with the ISO-362 specifications available in their respective category. However, the electric truck was unloaded.

### Comments on the medium heavy vehicles in all-electric mode and in hybrid mode

Significant differences can be noticed between the hybrid vehicles in electric mode and the electric vehicle (Figure 43), which are probably due primarily to vehicle size differences, as mentioned above. However, the electric truck is not systematically the quietest one in some

frequency bands, and particularly at high frequency (not illustrated). When compared with the CNOSSOS-EU model for Category 2, the noise emitted by the electric truck behaves similarly to the CNOSSOS rolling noise component in global levels, but differently in frequency. For both hybrid vehicles in electric mode, the contribution of the propulsion noise component plays a role at low speed. In its present definition, CNOSSOS-EU is inappropriate for predicting noise from this category of electric vehicle.

Global noise level differences occur between both hybrid vehicles in hybrid mode at low speed (Figure 44): the influence of the type of powertrain hybridization is not unlikely. Strong differences between the tested vehicles and CNOSSOS-EU raise the question of the representativeness of CNOSSOS-EU for these vehicles.

### Comments on CNOSSOS-EU for category 2

Before the EVs and HEVs consideration, there is the question of the characteristics of CNOSSOS-EU for medium heavy vehicles. As a matter of fact, the propulsion component of the model appears to be greater than rolling noise on the whole speed range in global levels. It is also significant in all octave bands, systematically exceeding rolling noise at least up to 70 km/h. This observation is definitely not in accordance with measurements performed by IFSTTAR with medium heavy ICE vehicles, and concerns primarily the rolling noise contribution. This issue needs to be deepened by considering a wider set of ICE vehicles of this category, as far as possible on other road surfaces. This is a prerequisite before considering the adequacy of CNOSSOS for EVs/HEVs. This item is examined in Section 0 to be clarified.

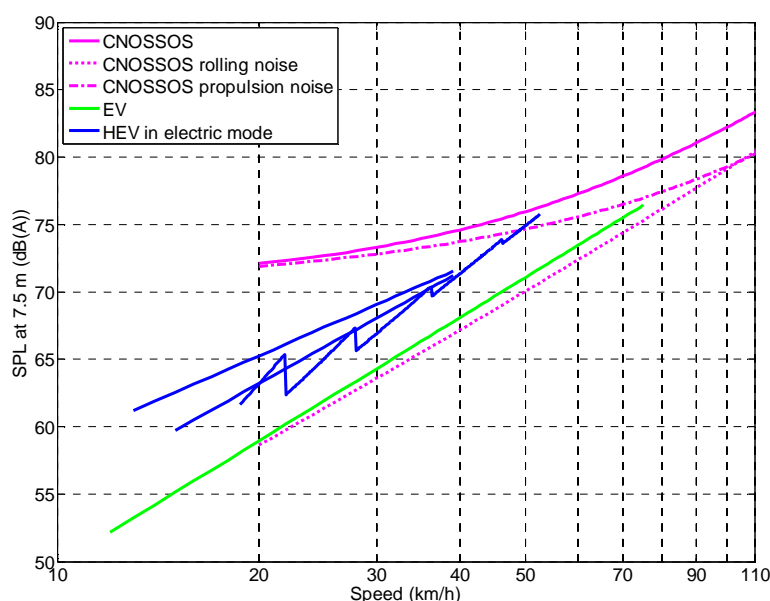


Figure 43: Data set of global noise measurement on medium heavy vehicles (EV and HEV) in all-electric mode at steady speed and CNOSSOS-EU model in reference conditions, at 7.5 m from the track centre (Category 2)



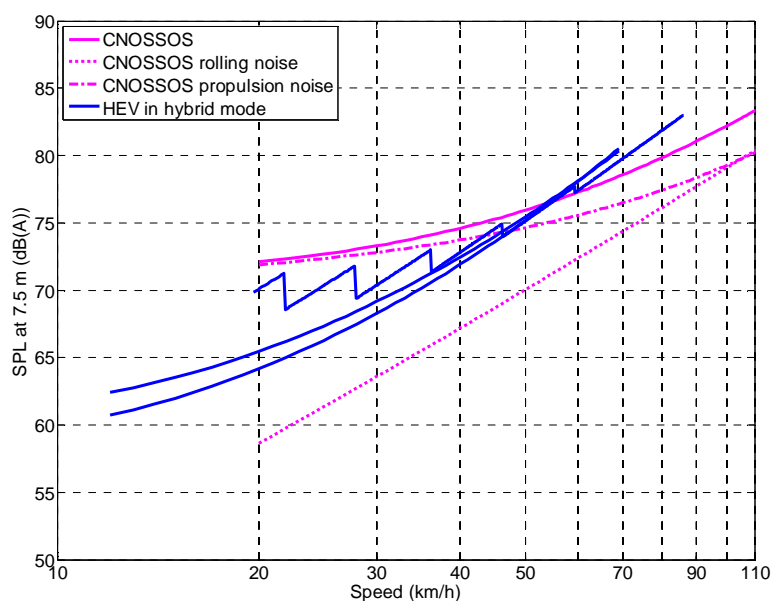


Figure 44: Data set of global noise measurement on medium heavy vehicles in hybrid mode at steady speed and CNOSSOS-EU model in reference conditions, at 7.5 m from the track centre (Category 2)

### 4.2.3 Main findings from the dataset

Since the observations rely on a restricted number of vehicles, they should be considered as indicative until a larger data collection is available.

#### Concerning noise emission of light electric vehicles (category 1):

The global noise emitted by all vehicles in electric mode follows a linear trend with  $\log(\text{speed})$ . The difference between the quietest and the noisiest vehicle is 4.5 dB(A) at any speed of the range 20-50 km/h. The noise increase is not linear in some frequency bands. In its present form, CNOSSOS-EU overestimates noise emission from light electric vehicles, particularly through the propulsion component at low speed, in all octave bands and, consequently, in global levels. A corrected version for EVs is required if a prediction of the noise impact from a traffic flow including EVs is needed.

#### Concerning noise emission of light hybrid vehicles (category 1):

The noise emitted by the few hybrid vehicles in the data collection exhibits a quite common behaviour.

In its present form, CNOSSOS-EU overestimates the propulsion noise component from the hybrid vehicles at low speed, mainly at high frequencies, whereas it predicts noise emission correctly at high speeds. The need for an adapted HEV version should be decided in the light of ICE car behaviour on the same test site. This is undertaken in section 0 of this report.

#### Concerning noise emission of medium heavy vehicles (category 2):

The analysis concerns few vehicles, evaluated on one test site.

For the vehicles in all-electric mode, large noise level differences are noticed between vehicles of dissimilar GVW and tyre size, with occasionally a modified ranking in frequency.

For the vehicles in hybrid mode, the type of hybridization might be a key parameter for the powertrain noise contribution.

In its present form, CNOSSOS-EU is not representative of the vehicles in electric or hybrid mode in the dataset.

**Concerning the model CNOSSOS-EU for ICE vehicles from category 2:**

The characteristics of the model CNOSSOS-EU for the vehicle category 2 raises question, about the weight granted to propulsion noise over the whole speed range relatively to rolling noise. In addition, test results available with ICE vehicles on the IFSTTAR test site are not consistent with this prediction. This item is deepened in Section 0.

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## 5 Adaptation of CNOSSOS-EU for light EVs and HEVs

CNOSSOS-EU provides a common noise emission model for all vehicles, composed of a propulsion noise component and a rolling noise component, each depending on the vehicle speed through two specific parameters in each octave band from 125 Hz to 4000 Hz (cf subsection 2.4.7). Vehicles are distributed in 4 categories, according to their size and axle number. Light vehicles correspond to category 1. A fifth category, named 'open category', has been left available for future needs. In each category, correction coefficients can be applied to the model components if the conditions deviate from the reference condition. These correction terms are either constant, speed dependent, or dependent on another parameter.

### 5.1 Proposal of CNOSSOS-EV for electric vehicles

The proposal for a description of light electric vehicles in CNOSSOS can be considered in two directions:

- either to define a new vehicle category
- or to recommend correction coefficients to the noise components available for category 1.

In the present situation where propulsion noise could not yet be clearly extracted from the pass-by measurement process, with small and sometimes even insignificant levels relatively to rolling noise, it would be mistaken to propose a definite speed-dependent mathematical expression describing the propulsion noise contribution in each octave. Until a more adequate statement is available, the present approach is proposed:

- the current model for category 1 is used,
- a constant correction coefficient is introduced on the propulsion noise in each octave for EVs,
- the rolling noise parameters given in CNOSSOS-EU are used until further directions are provided by WP3 of FOREVER.

This proposal implies that the EV model propulsion noise level increases in each octave with the same slope than ICE vehicles, which has no technical basis at this time but offers an easy as well as factually acceptable solution, as the following discussion shows. Consequently, within the reference conditions defined in CNOSSOS-EU, the EV propulsion noise is given by:

$$L_{WP,EV,i}(v) = A_{P,i} + B_{P,i} \left( \frac{v - v_{ref}}{v_{ref}} \right) + \Delta L_{WP,EW,i} \quad (34)$$

where

- $A_{P,i}$  and  $B_{P,i}$  are the official CNOSSOS-EU coefficients expressed in the octave band  $i$  for vehicle category 1, and for the reference speed  $v_{ref} = 70$  km/h.
- $\Delta L_{WP,road}$  is the correction coefficient to be introduced for EVs in the octave band  $i$

It was observed that ICE cars measured on the same site as the EVs behave slightly differently from CNOSSOS-EU. In order to use a common reference for the determination of the correction coefficients, other things being equal, it was thus decided to rely on these

measures of ICE cars conducted on the same test site. The IFSTTAR data, since they provide the wider speed range, were selected for this proceeding, the TRL results being displayed for checking consistency.

The principle of the approach involves the following steps in each octave band:

1. From IFSTTAR measurements on ICE vehicles, an ICE propulsion noise component similar to equation (28) is determined  $\Rightarrow L_{prop,ICE,i}(v)$
2. From IFSTTAR measurement on EVs, an EV propulsion noise component similar to equation (28) is determined  $\Rightarrow L_{prop,EV,i}(v)$
3. According to equation (34), the correction coefficient is given by the difference:  
 $L_{prop,EV,i}(v) - L_{prop,ICE,i}(v)$

All illustrations are provided as A-weighted maximum sound pressure levels at the distance of 7.5 m from the track centre (height 1.2 m).

### 1. Determination of the propulsion noise component for the ICE cars

Pass-by noise levels measured at 7.5 m with 11 ICE cars have been used (Figure 45). The distribution in octave bands is reported in Appendix D (Figure D12). This set of cars ranges from small to large passenger cars, including a SUV. Seven cars have a diesel engine and four have a gasoline engine, this disparity approximately reflecting car sales in France<sup>28</sup>.

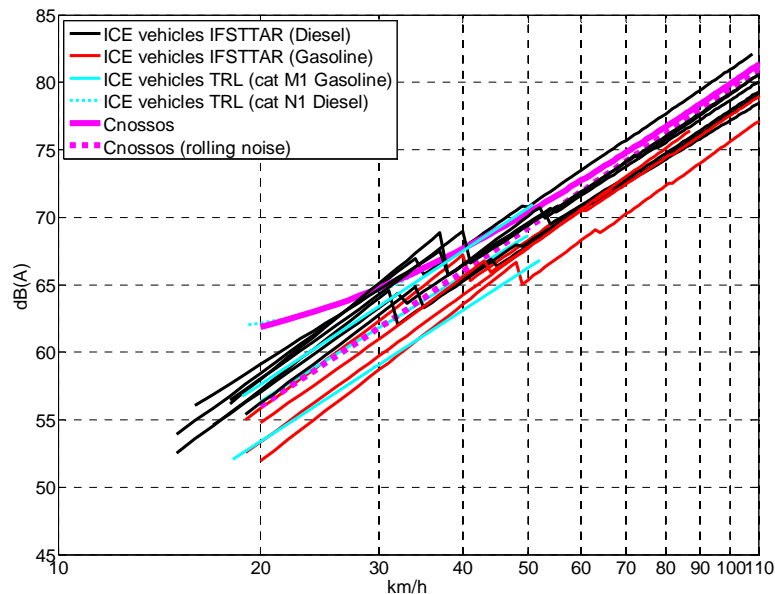


Figure 45: Data set of global noise measurement on ICE cars at steady speed and CNOSSOS-EU model in reference condition (Category 1) – Sound pressure levels at 7.5 m from the track centre

For each ICE car, the engine speed is known at each vehicle speed. Then, the total noise is decomposed in a powertrain noise component (function of the engine speed) and a rolling noise component (function of the vehicle speed) (Lelong, 1999).

<sup>28</sup> In 2012, diesel cars accounted for 73% of French car sales and gasoline engine for 25% (source: <http://www.ccfa.fr/Edition-no33-Annee-2012>)

In each octave, the total noise average  $L_{ICE,i}(v)$  from the 11 ICE cars is determined, as well as the average  $L_{roll,ICE,i}(v)$  of the rolling noise components. These represent the average ICE car of the set of cars.

Finally, the best fit for the propulsion noise model of the average ICE car is calculated by using:

$$L_{ICE,i}(v) = L_{prop,ICE,i}(v) \oplus L_{roll,ICE,i}(v) \quad (35)$$

with:

$$L_{prop,ICE,i}(v) = A_{prop,ICE,i} + B_{P,i} \left( \frac{v - v_{ref}}{v_{ref}} \right) \quad (36)$$

where  $A_{prop,ICE,i}(v)$  is the only unknown parameter, determined in each octave band through the optimisation process.  $B_{P,i}$  is given in CNOSSOS-EU (Category 1). Thus,  $L_{prop,ICE,i}(v)$  has the same trend as the CNOSSOS-EU propulsion component; only the intercept is modified. The resulting components are shown in Figure D13 (Appendix D).

## 2. Determination of the propulsion noise component for the EVs

In the same spirit, the average of the EV noise levels is calculated in each octave. The corresponding propulsion noise component is determined by fitting a 2-component model to the average data:

$$L_{EV,i}(v) = L_{prop,EV,i}(v) \oplus L_{roll,EV,i}(v) \quad (37)$$

where

$$L_{prop,EV,i}(v) = A_{prop,EV,i} + B_{P,i} \left( \frac{v - v_{ref}}{v_{ref}} \right) \quad (38)$$

$$L_{roll,EV,i}(v) = A_{roll,EV,i} + B_{R,EV,i} \log \left( \frac{v}{v_{ref}} \right) \quad (39)$$

with two unknowns  $A_{prop,EV,i}$  and  $A_{roll,EV,i}$ .  $B_{P,i}$  is the slope of the propulsion component given in CNOSSOS-EU. Two different tests have been carried out, implying a distinct choice of  $B_{R,EV,i}$ :

- **test 1:** the rolling noise slope is taken as in CNOSSOS-EU  $B_{R,EV,i} = B_{R,i}$
- **test 2:** the rolling noise slope is taken as for the average ICE car  $B_{R,EV,i} = B_{roll,ICE,i}$

Test 2 leads to an inconsistency at 63 Hz, with a probable transfer of all noise information on the rolling noise component. Differences between test 1 and test 2 are small in the other octave bands. For these reasons, the approach of test 1 is preferred. Anyway, as indicated previously, results at 63 Hz should be taken with caution, due to potential remaining background noise interference; they are displayed in italics in the final tables.

The resulting components obtained for the measured EVs are shown in Figure D14 (Appendix D). From 500 Hz to 2000 Hz, the estimated propulsion noise component is too low to be visible in the figure.

## 3. Determination of the correction coefficient

The correction coefficient is given by  $L_{prop,EV,i}(v) - L_{prop,ICE,i}(v) = A_{prop,EV,i} - A_{prop,ICE,i}$  which is a constant specific to each octave. In some octave bands, the estimated propulsion noise level

of the average EV is very small. In these cases, the correction coefficient has been arbitrarily limited to -15 dB(A).

The parameters proposed for a CNOSSOS-EV model are summarized below. The corresponding figures in octave bands and in global levels are provided. The resulting difference in global levels, on the propulsion noise component and on the total vehicle noise, as compared with CNOSSOS-EU for ICE cars, is also displayed.

### Summary of the proposal for CNOSSOS-EV, based on CNOSSOS-EU:

#### Electric vehicle propulsion noise emission model:

$$L_{WP,EV,i}(v) = A_{P,i} + B_{P,i} \left( \frac{v - v_{ref}}{v_{ref}} \right) + \Delta L_{WP,EV,i} \quad (40)$$

where

- $A_{P,i}$  and  $B_{P,i}$  are the official CNOSSOS-EU coefficients expressed in the octave band  $i$  for vehicle category 1, and for the reference speed  $v_{ref} = 70$  km/h.
- $\Delta L_{WP,road}$  is the correction coefficient to be introduced for EVs in the octave band  $i$ .

The values of  $\Delta L_{WP,road}$  are given in Table 9.

#### Electric vehicle rolling noise emission model:

As long as further rolling noise recommendations are not available from WP3, the use of the official CNOSSOS-EU model is advised.

Table 9: Correction coefficients  $\Delta L_{WP,EV,i}, \Delta L_{WP,road}$  for the propulsion noise component, to be applied to CNOSSOS-EU propulsion noise component for the light vehicles in all-electric mode

octave	63 Hz	125Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Correction coefficient	-5.0 dB(A)	-1.7 dB(A)	-4.2 dB(A)	-15 dB(A)	-15 dB(A)	-15 dB(A)	-13.8 dB(A)

Remark: the correction coefficients have been arbitrarily limited to -15 dB(A).

The figures presenting the model in octave bands are given in Figure 46. Although the approach relies on data within the range [20-90 km/h], the model has been extrapolated up to 110 km/h.

Finally, the CNOSSOS-EU model and the model proposed here for electric vehicles are compared in global levels in Figure 47. Noise level differences are given in Table 10 for several vehicle speeds.

Table 10: Noise level differences between the propulsion noise components (resp. the total noise) of the electric vehicle model and CNOSSOS-EU model, in global levels

Speed (km/h)	20	30	40	50	70	90	110
Propulsion noise $L_{EV} - L_{ICE}$ (dB(A))	-11,6	-11,7	-11,8	-11,9	-12,0	-12,1	-12,1
Total noise $L_{EV} - L_{ICE}$ (dB(A))	-5,1	-2,7	-1,6	-1,0	-0,6	-0,5	-0,4

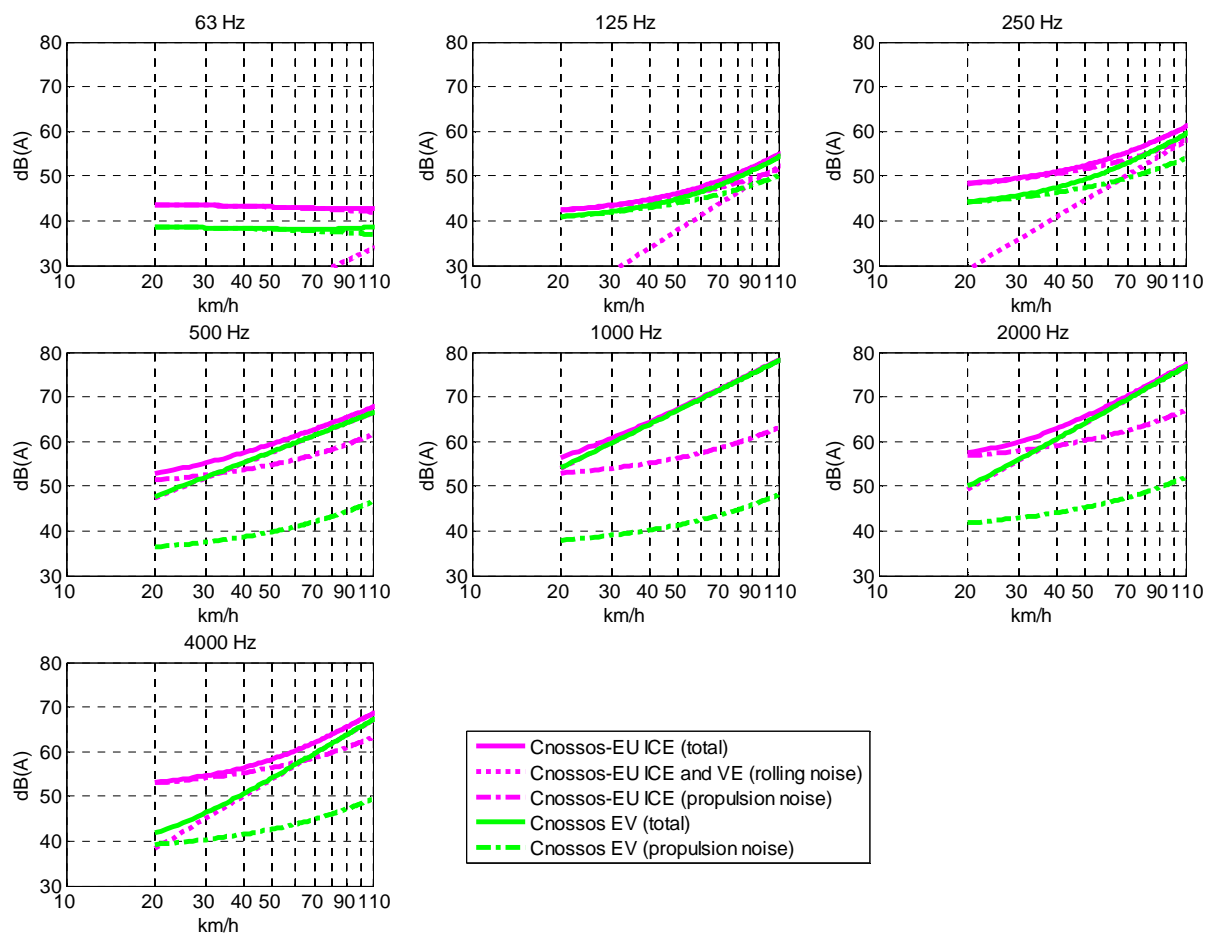


Figure 46: Comparison of CNOSSOS-EU (for ICE light vehicles) and CNOSSOS-EV (for electric light vehicles) noise components



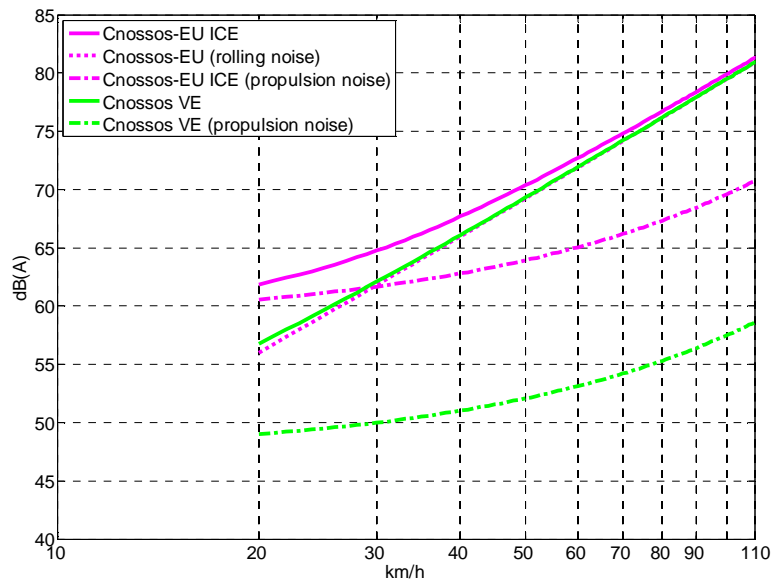


Figure 47: Comparison of CNOSSOS-EU (for ICE light vehicles) and CNOSSOS-EV in global levels

**Remark:** CNOSSOS-EU includes a correction term for accelerating or decelerating vehicles, in the vicinity of a crossing or a roundabout. This item could be determined later on for EVs and HEVs as an extension of the work performed in the project FOREVER.

## 5.2 CNOSSOS model for hybrid vehicles

Very few data from hybrid light vehicles is available. The noise emission from these hybrid cars is rather similar to the one from the ICE cars, in global levels (Figure 48) and in most octave bands (Appendix D, Figure D15).

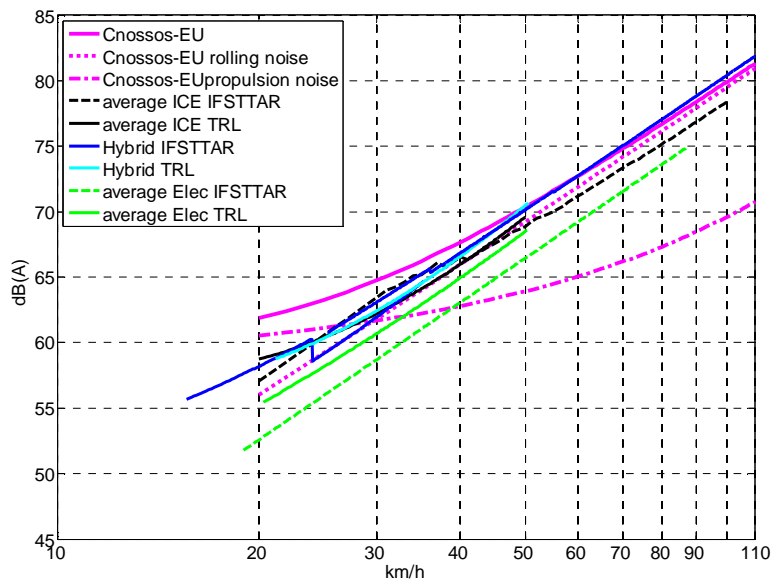


Figure 48: Comparison of the global noise measurement of the hybrid cars with the average ICE car at steady speed and CNOSSOS-EU model in reference condition (Category 1) – Sound pressure levels at 7.5 m from the track centre

**Proposal for the hybrid cars in CNOSSOS-EU:**

Considering on one hand the low number of hybrid vehicles available in the dataset, on the other hand the spreading of the ICE car results compared with the similarity in the noise emission from these ICE and hybrid cars, we recommend modelling the light hybrid vehicles like the ICE cars, by using also CNOSSOS-EU specifications for the hybrid cars. No correction is proposed.

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## 6 Investigation on CNOSSOS-EU for medium heavy vehicles (Category 2)

Complementary investigations have been made concerning vehicles defined within the CNOSSOS-EU method as Category 2 (medium heavy vehicles with a gross vehicle weight greater than 3.5 t with two axles and twin tyre mounting on rear axle).

The analysis reported in Section 4.2.2 on vehicles from Category 2 involved a limited number of vehicles, assessed on an IFSTTAR test facility: one small electric truck (investigated within the framework of FOREVER) and two hybrid vehicles (already available in the IFSTTAR database). For the vehicles in all-electric mode, large noise level differences were noticed between vehicles of dissimilar GVW and tyre size, with occasionally a modified ranking in frequency. For the vehicles in hybrid mode, the type of hybridization was suspected to be a key parameter for the powertrain noise contribution.

In its present form, CNOSSOS-EU is not representative of medium heavy vehicles in electric or hybrid mode from the measured dataset. The need for possible alternative modelling of these vehicles in CNOSSOS-EU depends to some extent on their acoustical behaviour in comparison with similar ICE vehicles. However, questions have arisen on the characteristics of CNOSSOS-EU for medium heavy ICE vehicles. As a matter of fact, the propulsion component of the model appears to be greater than rolling noise over the whole speed range in terms of global levels. It is also significant in all octave bands, systematically exceeding rolling noise at least up to 70 km/h. This observation differs from measurements performed elsewhere by IFSTTAR, primarily concerning rolling noise. Thus, it was considered necessary to deepen the investigation by considering a wider set of ICE vehicles in this category.

Measurement results provided by IFSTTAR have been considered first, concerning both controlled and statistical pass-by tests (Section 6.1). Since no other data from vehicles in this category was available from project partners to date, data found in other published literature has been analysed (Section 6.2).

### 6.1 Assessment on noise emission from ICE medium-heavy vehicles

Two IFSTTAR datasets have been examined. The first one relates to extensive controlled pass-by measurements performed on two vehicles in the past few years, the second one concerns statistical pass-by measurements carried out in 2004.

#### Controlled pass-by levels

Two diesel-powered vehicles have been investigated on the IFSTTAR test track with a DAC 0/10 road surface. They correspond to categories M3 and N3 according to the EU classification. Among the various driving conditions explored, only constant speed pass-bys are considered here. A-weighted maximum sound pressure levels have been measured with microphones at standard position (distance 7.5 m, height 1.2 m) (AFNOR, 2000). Results as a function of vehicle speed are shown in Figure 49 (black and blue solid lines). The discontinuities in the curves are due to the influence of the gear engaged on the engine speed and consequently on the propulsion noise. For one vehicle, the propulsion noise and rolling noise components are also plotted (black discontinuous lines).

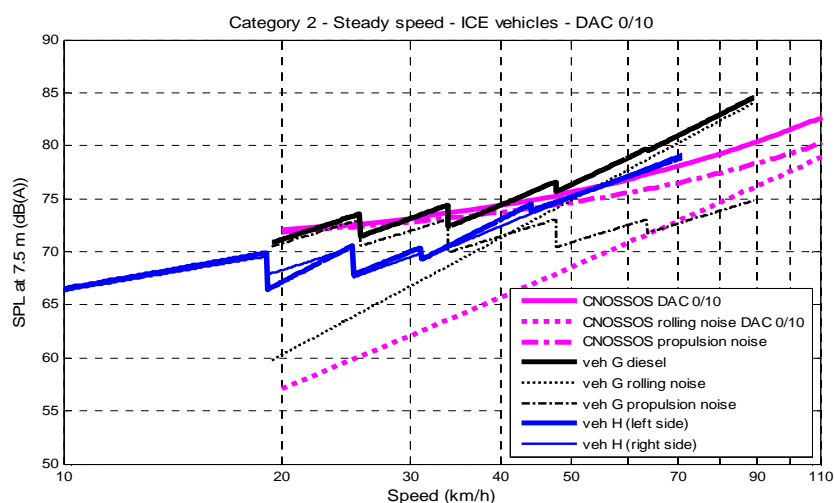


Figure 49: Maximum global sound pressure level for two ICE vehicles of category 2 on a DAC 0/10 road surface (blue and black lines) – CNOSSOS-EU model corrected for a DAC 0/10 road surface (pink lines) – SPL in dB(A) at 7.5 m

For comparison, a corrected CNOSSOS-EU noise emission model has been superposed in Figure 49. Since CNOSSOS-EU provides noise emission coefficients under reference conditions referring to an average road surface of DAC 0/11 and SMA 0/11, correction terms have been determined for DAC 0/10. CNOSSOS-EU recommends applying a spectral correction factor on rolling noise for dense surfaces which differ from the reference conditions. This correction factor is given by:

$$\Delta L_{WR,i}(v) = \alpha_i + \beta \log\left(\frac{v}{v_{ref}}\right) \quad (41)$$

where  $\alpha_i$  is the correction in the octave band  $i$  at the reference speed  $v_{ref}$  and  $\beta$  is the speed effect on rolling noise reduction (assumed independent of frequency). The CNOSSOS-EU method allows the user to use their own road surface data. In the present case, the following procedure has been applied here:

- For the determination of the coefficients  $\alpha_i$ , data from DEUFRABASE<sup>29</sup> has been used. This software can provide the  $L_{Aeq}$  in third-octave bands (from 100 Hz to 4000 Hz) for various pavements and one truck at the reference speed 80 km/h. Calculations have been made for a DAC 0/10<sup>30</sup> and a SMA 0/11 road surface respectively. Differences between the noise levels associated with these road surfaces have been deducted and stated in octave bands from 125 Hz to 4000 Hz<sup>31</sup>. The coefficients  $\alpha_i$  are given in Table 11.
- DEUFRABASE does not provide any information on the speed index of the road surfaces. By reference to the French method NMPB08 which recommends the same speed index for heavy trucks on all road surfaces (trend  $30 \log v/80$ ) (Hamet, 2010)), the coefficient  $\beta$  has been taken as  $\beta = 0$ .

<sup>29</sup> <http://deufrako.bast.de>

<sup>30</sup> French name: BBSG 0/10.

<sup>31</sup> The third-octave 5000 Hz is not considered in the DEUFRABASE. Since the noise spectra regularly decrease in the high frequency range, the spectrum levels at 5000 Hz have been arbitrarily inferred here by extrapolating the data according to the high frequency trend of the respective spectra.

Table 11: Correction coefficients  $\alpha_i$  applied to the rolling noise component of a DAC 0/10 by reference to a SMA 0/11 road surface, for medium heavy vehicles

Octave $i$	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Correction $\alpha_i$ in dB	+0.4	-1.5	-1.4	-1.6	-1.4	-0.6

In global levels, the rolling noise component for CNOSSOS-EU corrected for DAC 0/10 is reduced by 1.5 dB. Since both road surfaces are dense, no correction is required on the propulsion noise component.

In Figure 49, it can be observed that the CNOSSOS-EU propulsion noise component is relevant for predicting the louder vehicle and overestimates the other one. However, the rolling noise is clearly undervalued by at least 4-5 dB(A) by CNOSSOS-EU. This is particularly obvious in the octave 500 Hz and more widely from 250 Hz to 2000 Hz for these two vehicles.

### Statistical pass-by noise levels

The data presented are results from an experiment carried out in 2004 along a high speed road. Noise levels from 14 two-axle trucks in the traffic, corresponding to medium heavy vehicles from CNOSSOS-EU vehicle category 2, were recorded according to standard SPB procedure (ISO, 2002). The road surface was a very thin asphalt concrete 0/6 Type 2<sup>32</sup>. This surface, although not porous, is slightly acoustically absorbing. Maximum A-weighted SPL are plotted as a function of vehicle speed in Figure 50, together with CNOSSOS-EU corrected for this road surface as described below.

The correction  $\Delta L_{WR,i}(v)$  for rolling noise in each octave  $i$  has been determined in the same way as previously described. The coefficients  $\alpha_i$  are given in Table 12 and again  $\beta = 0$ . The global rolling noise reduction of this road surface comparatively to the reference condition is -5.4 dB.

Since the road surface offers absorbing properties, a correction has also been included on the propulsion noise. For porous surfaces, CNOSSOS-EU method proposes a correction factor given by:

$$\Delta L_{WP,i} = \min\{\alpha_i ; 0\}$$

with the  $\alpha_i$  being identical to those for rolling noise.

<sup>32</sup> French name : BBTM 0/6 Type 2.

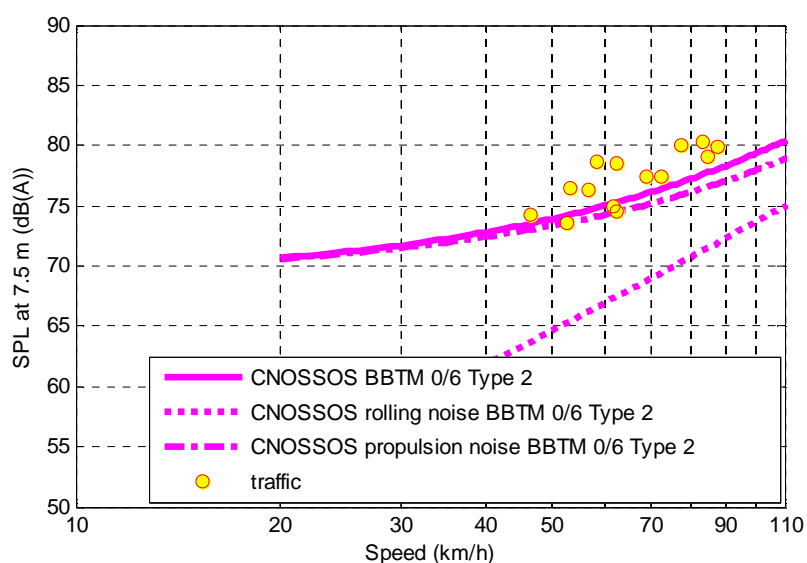


Figure 50: Maximum global sound pressure level for ICE vehicles of category 2 measured in the traffic on a very thin AC 0/6 Type 2 road surface (yellow circles) – CNOSSOS-EU model corrected for a very thin AC 0/6 Type 2 road surface (pink lines) – SPL in dB(A) at 7.5 m

Table 12: Correction coefficients  $\alpha_i$  applied to the rolling noise component of a very thin AC 0/6 Type 2 by reference to a SMA 0/11 road surface, for medium heavy vehicles

Octave $i$	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Correction $\alpha_i$ in dB	-2.2	-4.2	-3.4	-6.1	-7.3	-6.3

In order to estimate the sole absorption effect of this road surface without including any chipping size effect, DEUFRABASE has been used here to determine the noise spectrum for one truck at 80 km/h on a very thin AC 0/6 Type 2 (absorbing) as compared with a very thin AC 0/6 Type 1 (very few absorbing) surface. Then the correction factors have been determined according to the same procedure as before for rolling noise. The propulsion noise correction factors are listed in Table 13. In global levels, the noise reduction on the propulsion noise is -1.3 dB.

Table 13: Correction coefficients  $\alpha_i$  applied to the propulsion noise component of a very thin AC 0/6 Type 2 by reference to the CNOSSOS-EU reference condition, for medium heavy vehicles

Octave $i$	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Correction $\alpha_i$ in dB	-0.8	-0.6	-0.6	-1.5	-1.9	-2.0

On average, CNOSSOS-EU when corrected for the road surface underestimates the global vehicle noise levels. This mainly results from the behaviour in the octave 125 Hz to 500 Hz (Figure 51). It is valuable to notice on the CNOSSOS-EU model that the propulsion noise exceeds the rolling noise at all frequencies over the whole speed range. These components cannot be separated from the measurement results. However, it can be suspected that CNOSSOS-EU undervalues the rolling noise contribution at least in the 500 Hz octave, or perhaps even in the lower octave bands.

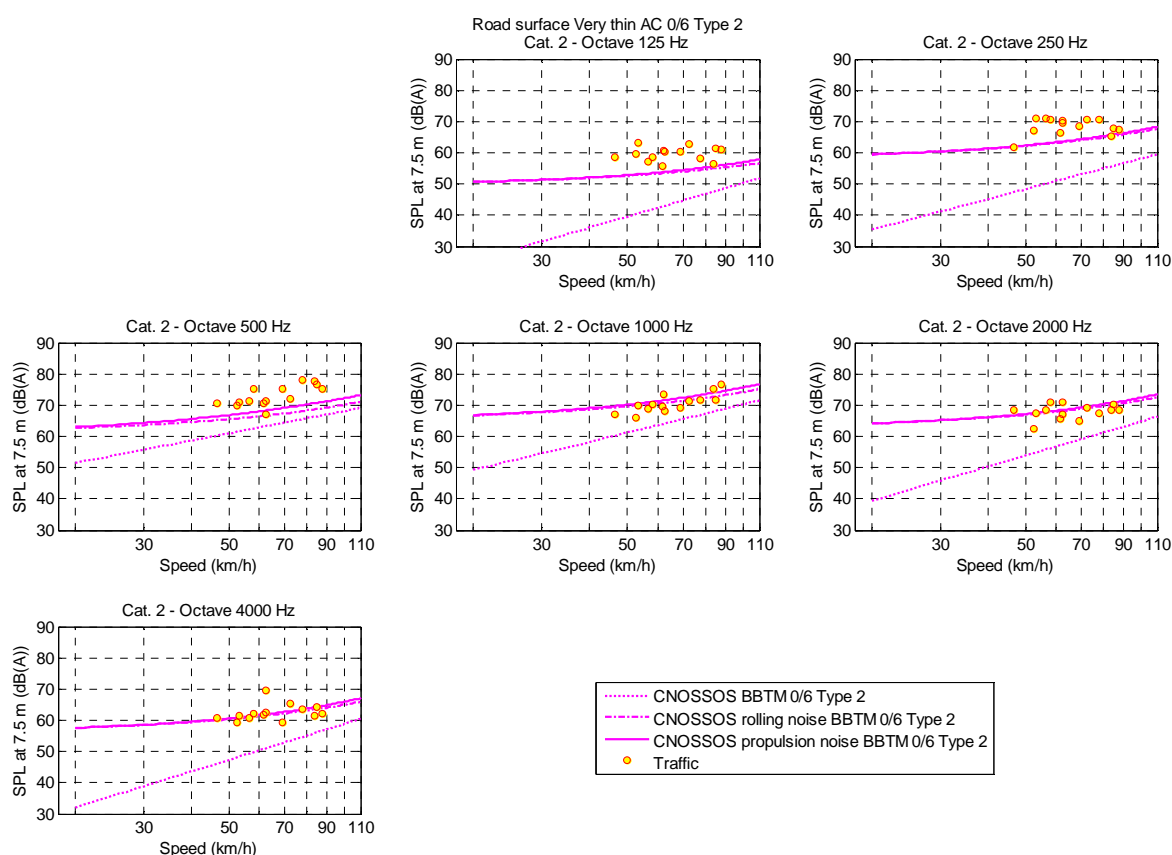


Figure 51: Maximum sound pressure level for ICE vehicles of category 2 measured in the traffic on a very thin AC 0/6 Type 2 road surface (yellow circles) – CNOSSOS-EU model corrected for a very thin AC 0/6 Type 2 road surface (pink lines) – SPL in dB(A) at 7.5 m in octave bands

## 6.2 Noise emission from ICE medium heavy vehicles: literature review

Similar data has been sought in the literature and only few studies could be found. First, the cruise-by SPL of a Scania two-axle truck (in accordance with the 80 dB(A) noise limit), measured in CPB conditions, is provided in a paper by U. Sandberg (Sandberg, 1992) and displayed in Figure 52. The road surface is indicated as being a smooth DAC with a maximum chipping size 12-16mm. On this figure the CNOSSOS-EU model in reference road surface conditions is also drawn for comparison. Despite road surface formulation differences, they may be considered as acoustically similar for heavy vehicles<sup>33</sup>.

<sup>33</sup> Private communication (U. Sandberg).



Nevertheless, the measurement results are definitely larger than CNOSSOS-EU at high speeds.

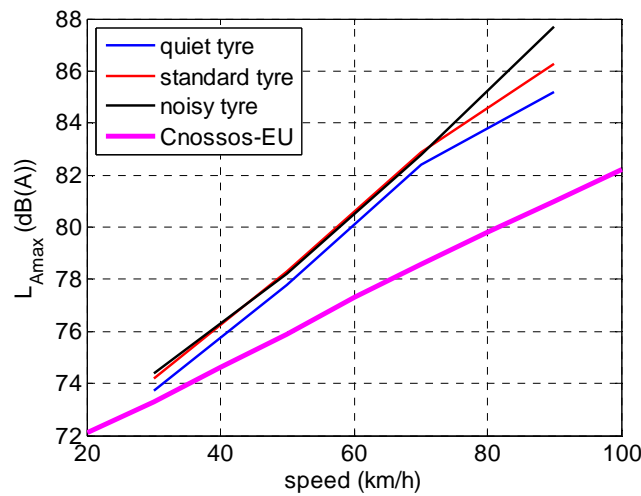


Figure 52: CPB noise levels for a two-axle truck (Scania G93) [Data from (Sandberg, 1992)] – Cruise-by on a smooth DAC with max. 12-16mm chippings and 3 tire types – CNOSSOS-EU in reference conditions.

The reference book by U. Sandberg and J. Ejsmont provides a figure with SPB sound pressure levels split up into vehicle types, among which heavy 2-axle vehicles, measured on a DAC 16mm surface (indicated as smooth) (Sandberg & Ejsmont, 2002). These vehicles are likely to be mostly heavy trucks and buses, moreover meeting the former 84 dB(A) noise limit. This result is duplicated in Figure 53 below. The CNOSSOS-EU model in reference condition has been manually sketched for vehicle category 2, to be compared with the measurement results plotted by blue circles and the blue regression curve.

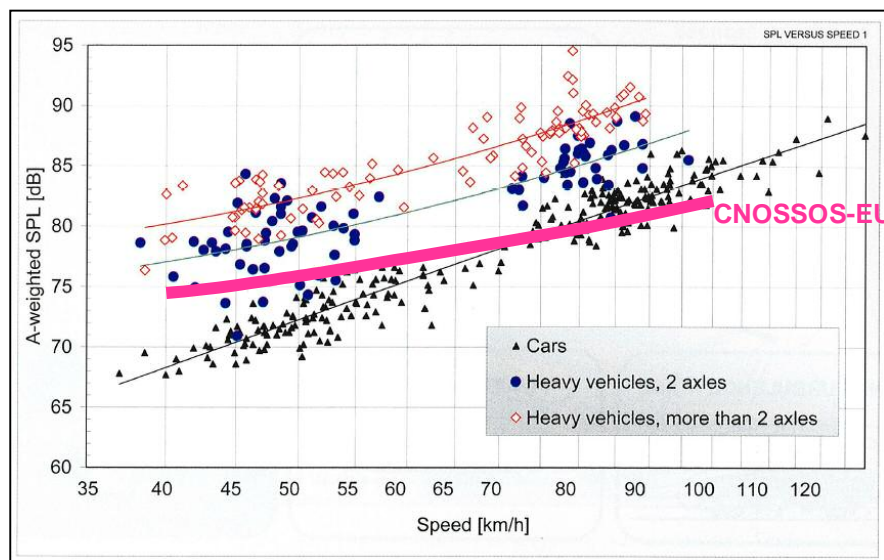


Figure 53: SPB noise levels for different types of vehicles on a smooth asphaltic concrete (DAC 16mm) (The figure is taken from (Sandberg & Ejsmont, 2002)) – in pink colour: CNOSSOS-EU in reference condition for category 2 (manually drawn).

There is a rather strong consistency between the sound levels measured on the cruising truck of Figure 52 and the corresponding regression curve in Figure 53, at least at high speed, despite a conformity to likely different noise limits. Considering noise statistics on road surfaces (Hamet, 2010), it turns out that the discrepancy observed between these results and the CNOSSOS-EU model is likely not due solely to road surface differences.

Another literature result has been taken from a German report by H. Steven, which includes a wealth of measured data and statistics on vehicle noise emission (Steven, 2005). Among these, a figure presents the noise levels from free flowing trucks with up to 3 axles, measured on DAC 0/11 or SMA 0/11 road surfaces. This figure is duplicated in Figure 54, where the blue circles refer to free-flowing trucks and the blue line is the corresponding regression line. The accelerating driving condition is disregarded here. The CNOSSOS-EU model is manually sketched on the figure. Despite similar road surface types, CNOSSOS-EU undervalues the average noise level by at least 5 dB(A) at 80-90 km/h. It must be noted that it is not possible to identify the contribution to this difference from heavy vehicles with 3 axles, which are likely to be operating to a different gear/engine speed relationship than the two-axle vehicles, with a possible effect on noise at low and medium speeds.

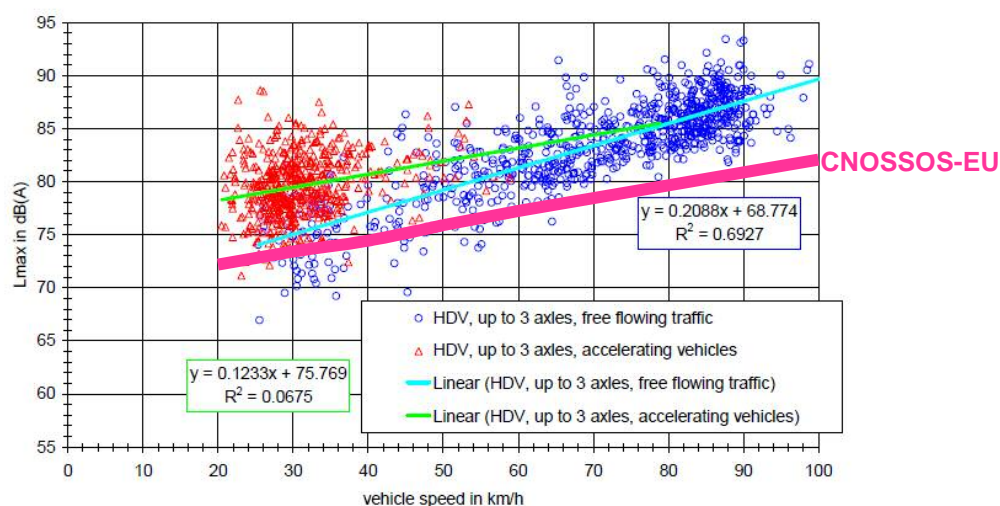


Figure 54: SPB noise levels for heavy vehicles up to 3 axles on DAC 0/11 and SMA 0/11 (The figure is taken from (Steven, 2005)) – in pink colour: CNOSSOS-EU in reference condition for category 2 (manually drawn).

### 6.3 Discussion

After considering the pass-by noise levels from the measurements performed on medium heavy electric and hybrid vehicles and comparing them with the CNOSSOS-EU model for vehicle category 2, CNOSSOS-EU seems to mispredict noise levels for this test site. In particular, the rolling noise prediction seems to be underestimated. In addition, it was noticed that the CNOSSOS-EU rolling noise of category 2 is quieter than the propulsion noise in dB(A) up to 90 km/h in global levels and 70 km/h (or beyond) in octave bands. Thus, a further analysis was conducted to compare CPB and SPB noise results from medium heavy 2-axle ICE vehicles with CNOSSOS-EU.

Two experiments carried out by IFSTTAR and some other results available in the literature agree on a possible underestimation of the CNOSSOS-EU rolling noise for a correct prediction of the pass-by noise measured on medium heavy ICE vehicles. The discrepancy

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may exceed 5 dB(A) at high speed. Thus, the trend observed here tends towards a modification of the balance between propulsion and rolling noise through increasing the rolling noise contribution. Since the amount and variety of the datasets investigated here are still limited, it would be worth widening the analysis in order to ascertain conclusions to be drawn both on propulsion and rolling noise contributions, by investigating current medium heavy vehicle fleets in circulation on various roads. Any proposal for a correction of CNOSSOS-EU for medium heavy EVs and HEVs would only subsequently make sense.

The opportunity to use the “open category” of CNOSSOS-EU has not been retained here: the availability of data emission from only three vehicles, tested on a single road surface, does not form a statistically representative sample to derive a sensible correction, even tentatively as a simple guideline.

## 7 Perception study

The standard approach to assessing vehicle noise emission is to use time averaged dBA based assessment methods (including band limited measures). It can often be the case that these measures fail to differentiate between vehicle types and in particular fail to accurately represent the change in noise character associated with electric vehicles. While the majority of people are familiar with road traffic noise, the decibel scale used to objectively describe predicted improvements or deteriorations of a particular situation are difficult to translate into a subjective description. Current methods of disseminating this information rely on noise mapping, the documentation of which can be difficult to follow especially for non-specialist readers. Therefore difficulty has been encountered when communicating noise data to the general public. In order to understand the likely reaction of a community to a change in the nature of the noise emission from a national route way this project has utilised a tool which immerses a participant in the acoustic environment of a national route way.

A key aim of the research has been to develop a controllable model of various road traffic mixes on a national route way. Using this approach it has been possible to investigate the effect of increasing percentages of electric vehicles as a source of the noise emission. As a start point for this process it was desirable to utilise the standard pass-by measurement data. There are detailed databases of this type of experimental measurement already available and further experimental campaigns have been conducted in the framework of this research project. The challenge therefore was to utilise these single mono recordings to generate an auralised road traffic environment in a rigorous and repeatable way. This process involved a combination of experimental noise measurement on IC and on EV test vehicles, a process of source modelling and software based 3D auralization tools.

Auralization is the process of digitally processing sounds so that they appear to come from particular locations in three-dimensional space, with the goal of simulating the acoustic field experienced by a listener within a natural environment. The auralization of traffic noise comprises two separate topics of research: Vehicle Noise Emission and Auralization Techniques. Vehicle noise emission is a research topic of considerable interest and has been researched widely through academic research and also through the research of the car manufacturing industry. However, auralization is a relatively new research area for road noise assessment and as a tool is unfamiliar to many in the industry.

In this research project the data from pass by tests has been utilised and passed through the following processing procedure to generate the auralizations:

1. Pass-by test data is de-Dopplerised and corrected for attenuation effects
2. Data is truncated to a region relatively close to the pass by microphone approximately +/- 25m
3. A simple model of directivity is achieved by splitting the test data into sections before and after the pass by point
4. Source spectra are calculated for the two regions
5. These source spectra are utilised to generate mutually uncorrelated source signals
6. The source signals are processed to apply Doppler and attenuation effects equivalent to a vehicle travelling on a stretch of national road
7. The signals are auralized using a database of Head Related Impulse Responses (HRIRs)
8. A database of driving conditions is used to generate a road traffic profile from the auralized source signals

The sound files generated from the above process are then used in studies of human perception and acceptability. The aim is to assess how people living close to national roads might subjectively respond to increases in the proportion of EVs in passing traffic. Auralizations of road traffic noise have been produced that include following proportions of EVs 0%, 20%, 40%, 60%, 80% and 100%. Additionally bandpass filtered version have been produced to investigate the frequency range responsible for the change in subjective response.

Each of the above steps is outlined in detail in the following sections.

## 7.1 Correction of Pass-by data

The first step in the correction of the pass-by data is to remove the Doppler and attenuation effects in order to produce a “stationary” vehicle source. This process utilises a standard approach (Dowling, 1983) based on the source angle and radius from the point of reception. The delay and attenuation are calculated according to equation (41) and the source signal is corrected to remove these effects.

$$D = \frac{R/c}{(1 - M^2)(M \cos \Theta + \sqrt{1 - M^2(\sin \Theta)^2})} \quad (42)$$

$$A = 4\pi R \sqrt{1 - M^2(\sin \Theta)^2}$$

D = delay, A = attenuation, R = radius to source, M = Mach number,  $\Theta$  = angle to source

This process produces a corrected signal which is equivalent to a hypothetical stationary source in front of the microphone for the duration of the pass-by. This procedure is not valid when the vehicle is too far from the microphone and the vehicle speed and position are not accurately known. Additionally the signal to noise ratio is higher when the vehicle is further from the pass-by microphone. Therefore the signal is truncated to a region which can be considered to be close to the pass-by microphone. The definition of the region where the signal can be de-Dopplerised is not well defined and in these tests a conservative estimate of the region was made where the signal to noise ratio of the pass-by was well above background levels. Further work at TCD will investigate the upper limit of this range in graduate research projects. In the pass-by tests considered the vehicle was travelling at 90kph, i.e. ~25m/s, and the data was truncated to a region +/- 25m from the pass-by microphone.

Even though the source can now be considered to be “stationary” there are still variations over the course of the signal due to the change in directivity of the noise as the source is approaching and receding from the pass-by microphone. In particular the exhaust noise of an IC vehicle is highly directional and dominates after the vehicle has passed the microphone, in this case the second half of the new “stationary” signal.

In order to account for a basic measure of this directivity the measured signal is split in half at the point where the vehicle passes in front of the microphone. In principle the measured signal could be split into multiple regions to account for a change in directivity over a wider range of angles. In this case however the time constraints on the processing necessitated a simpler approach.

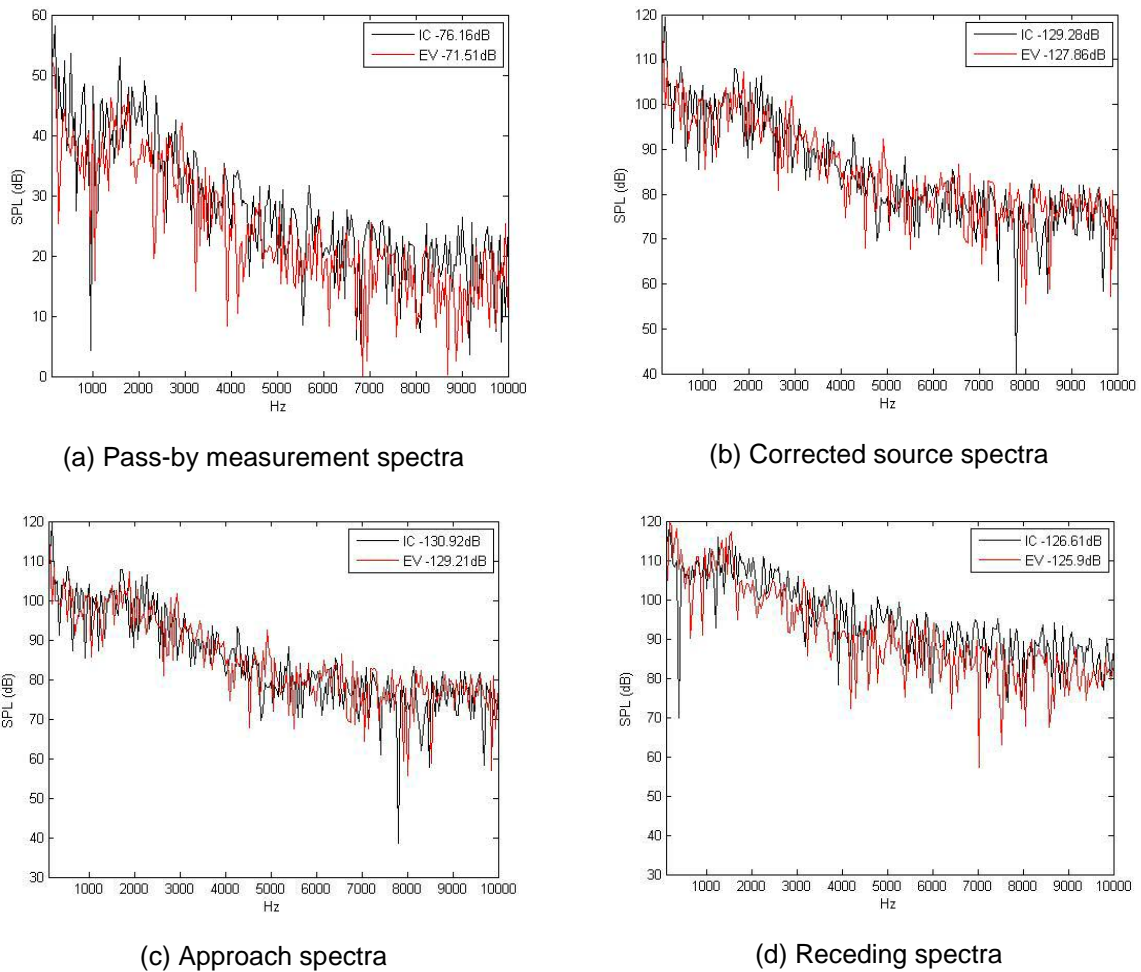


Figure 55: Application of the correction procedure to the pass-by data

Figure 55 shows the application of the correction procedure to the data from the pass-by measurements. Figure 55(a) shows the calculated source spectra and OASLP for the two second section of the pass-by data. Figure 55(b) shows the source spectra and OASPL after Doppler and attenuation effects have been removed. The final parts of the figure (c) & (d) show the spectra as the vehicle is approaching and receding from the measurement point.

Using these two halves of the signals high resolution frequency spectra are generated in a custom Matlab implementation with a resulting resolution of less than 1Hz. These measured spectra are the basis for the subsequent generation of synthesised vehicle noise.

## 7.2 Generation of Source Signals

The pass-by test data has generated accurate source spectra for the regions where the vehicles are approaching and receding from the road side microphone. These spectra can now be used to generate time domain signals of a pass-by for each vehicle. Since these generated signals are used to produce a mix of vehicles in a road traffic environment it is desirable that the generated signals are uncorrelated in order to eliminate any potential acoustic artefacts due to their interaction.

This is achieved by applying a random phase to the spectra during the inverse Fourier transform procedure:

$$S(x, t) = IFT[\sqrt{K(\omega)}e^{-iX(\omega)}] \quad (43)$$

S = Generated source signal, K( $\omega$ ) = Measured Spectra,  
X( $\omega$ )=Random variable between 0-2 $\pi$

The resolution of the spectra was such that the inverse Fourier transform produced 10 seconds worth of data at 44.1kHz. This was chosen as being sufficient to generate 250m worth of pass-by data at the chosen speed of 90kph.

This source signal was now corrected for Doppler and attenuation effects according to Equation 42. The source levels are calibrated to produce the correct far field levels corresponding to the pass-by test data. This is achieved by measuring the levels of the generated sound files using a binaural mannequin head. A system calibration is conducted for the PC and headphone system to be used for presentation of the sound files and used to calibrate the levels of the source prior to Doppler and attenuation effects.

The data used for the generation of these source signals corresponds to the measurements performed on the IFSTTAR test site. This approach allowed for homogeneity in the WP2 results where a large part of the measurements have been carried out in almost the same test conditions. In order to reduce variability and insure that any variation in participant responses was due solely to the change in the character of EV noise emission only two vehicle types were used in these auralizations. A single IC and a single EV pass-by measurement were used for generating the road auralizations.

In order to achieve these corrections to the far field sound level the geometry of the road environment was required. A basic 4 lane road way was considered with vehicles moving from left to right in the lanes closest to the point of reception and from right to left in the two lanes furthers from the point of reception. The dimensions of the road were considered to be those shown in Figure 56.

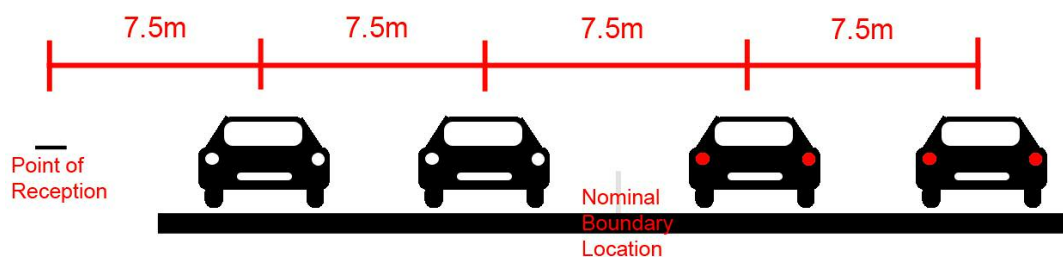


Figure 56: Road layout

The road traffic environment was generated so that 10 vehicles with a random spacing of between 1.7-2.3 seconds between vehicles were placed in each lane. The road environment was considered to be 250m long with the point of reception at the half way point i.e. 125m. The sound files were generated beginning with the point when two vehicles had already passed the point of reception in the near lane and ended when there were still two vehicles yet to pass the point of reception. This produced a constant steady traffic flow and sound files of approximately 30 seconds in length.

Various road traffic mixes of ICs and EVs were then produced. The percentage of EVs was then varied from 0% to 20%, 40%, 60%, 80% and 100%. This corresponded to 0, 2, 4, 6, 8 and 10 EVs in each lane of the road environment.

The participant study was planned to investigate the overall change in response to the noise of the road environment. It was also considered that further efforts could be made to quantify what aspect of the change in EV noise emission was responsible for a given change in response by the participants. Examining the audio files and source spectra it was decided to produce another set of road environments where the sounds had been filtered into distinct frequency bands. This approach allows the frequency ranges, i.e. low, mid or high, which are responsible for the change in subjective responses to be identified.

With this approach in mind the sound files were filtered for the follow frequency ranges: 0-100Hz, 100-500Hz, 500-2000Hz and 2000Hz and above. A comparison of the original and filtered spectra for the 0% EV and for the 100% EV case traffic mix is presented in Figure 57. A qualitative analysis of the resulting sound files shows that the main exhaust tones of the IC are contained in the 100-500Hz and 500-2000Hz frequency range and that this approach has separated the regions containing the most obvious difference in noise emission from the EV case. The presence of the engine tones is clearly distinguishable to the human listener. The presence of these tones can be distinguished in the filtered spectra of Figure 57(b) comparing the IC and EV spectra. The participant study investigates if these differences produce any subjective differences in human response.

The importance of engine tones in this frequency has been demonstrated in the past for motorcycle noise exposure (Kennedy, 2013). The importance of the tonal content of the noise in subjective responses may prove to be significant when considering EV noise emission.

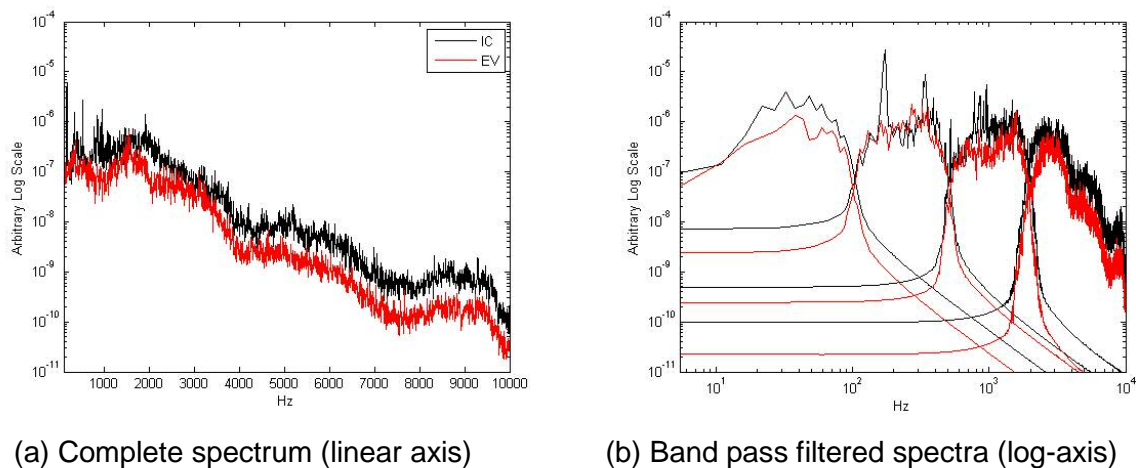


Figure 57: Original (a) and Filtered (b) spectra of road traffic environment for 0% (black) and 100% (red) EV mix

### 7.3 Auralization of Road Traffic Profiles

In order to apply the spatializing process a public-domain database of high spatial resolution Head-related Impulse Response functions (HRIRs) was utilised. This was the CIPIC database measured at the U.C. Davis CIPIC Interface Laboratory. This database includes extensive measurements of the standard KEMAR binaural head to generate a general HRIR



database. In this work we make use of these KEMAR HRIRs for the generation of the spatialized sound files.

The process of applying HRIRs to a stationary sound source is straight forward and equivalent to filtering the left/right ear stereo channels with two separate filters. When a sound source is moving this process is more complex and in principle would require a unique HRIR for every location of the sound source relative to the listener. In the situation of a vehicle pass-by the angles which a vehicle moves through are greater than  $\pm 80^\circ$  in the horizontal plane in front of the listener. The standard database available only has a finite selection of positions available in this front horizontal plane and therefore another approach is required.

One of the most successful approaches to spatializing sounds which move relative to the listener is known as Ambisonics. This approach has been utilised in music and entertainment applications since the late 70s and was pioneered in many applications by Michael Gerzon (Gerzon, 1973). This approach was hindered in its early years as it required complex hardware implementations of the algorithms to playback the spatialized sound. In modern times software implementations have achieved improved real time processing in a manner more suitable for practical research projects (Gorzel, 2010). This project has utilised a custom Matlab software program to implement the Ambisonic approach.

In brief the Ambisonic approach may be described as a technique for accurate recreation of sound fields through the resolution of spherical harmonic equations. These equations determine the incident sound field on a sphere surrounding the listener which is dependent only the source azimuth and elevation angles. The important point is that this approach allows a dynamic moving source to be represented from an array of fixed virtual speaker locations each of which has its own fixed HRIR. The complete sound field is perfectly represented by a sum of the outputs of these virtual speakers. The situation is shown in Figure 58.

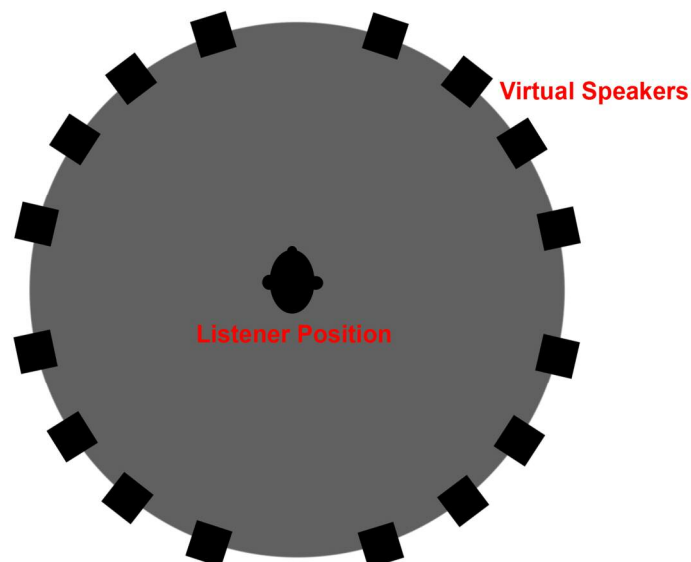


Figure 58: Ambisonic implementation of an array of 16 virtual speakers

The source signals have already been correctly processed for Doppler and attenuation effects in the previous steps. Now the source angle and elevation is calculated and used to encode the information that comes from each of the 16 virtual speaker locations. The final step is to combine the outputs of those speakers for the listener, a process known as decoding, and apply the correct HRIR for the output of each speaker location.

At this point a fully spatialised sound field has been produced. This process is applied to the entire database of vehicle noise sources generated in the previous steps. From this new database of sounds a road profile can be assembled and a traffic noise environment generated.

The road layout used has been described above and consists of 4 lanes of traffic. Sound files were generated in which ten vehicles move relative to the listener in each lane of traffic. Of these ten vehicles there were varying percentages of EVs in each sample.

## 7.4 Participant Testing

Sound files generated from the data above were used in studies of human perception and acceptability. The aim was to assess how people living close to national roads might subjectively respond to increases in the proportion of EVs in passing traffic. Auralizations of road traffic noise were produced that include 0%, 20%, 40%, 60%, 80% and 100% EVs in the traffic mix. These auralizations were assessed experimentally by participants who were told they are hearing the sound of traffic passing a residential area on a major road. The auralizations were each rated through a series of perceptual dimensions, such as “pleasant – unpleasant” and “relaxing - disturbing”, as reported in previous work by (Guidice, 2010).

Specially written software allowed participants to adjust a series of sliders whilst listening to the sounds. Each slider moved between endpoints labelled with opposite anchor words, as detailed in Table 14. This provided, across participants, mean ratings on each scale for each of the auralizations. Figure 59 shows the user interface for the participant studies.

Table 14: Anchor words used in participant study

Pleasant	Unpleasant
Relaxing	Disturbing
Dirty	Clean
Loud	Quiet
Repellent	Attractive

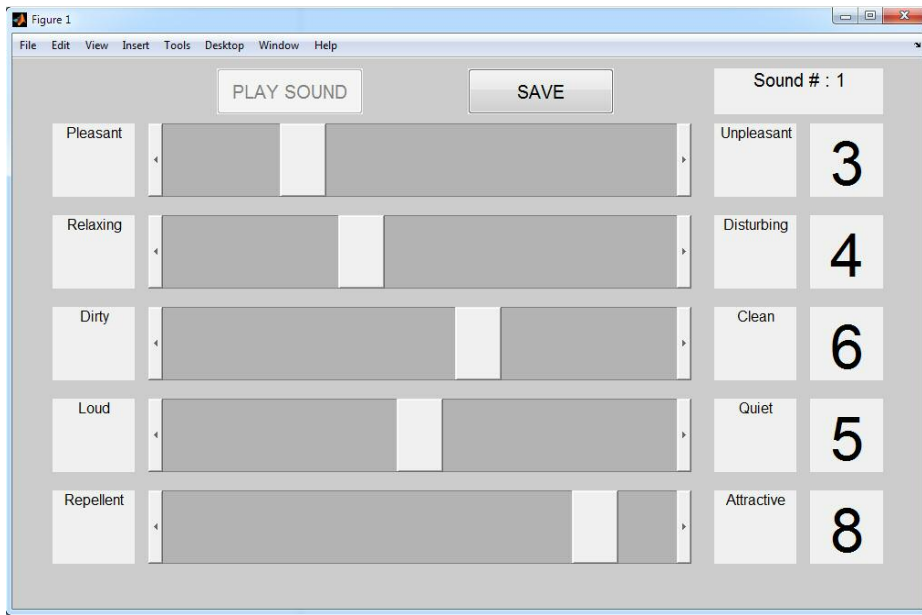


Figure 59: User interface used in participant testing

## Results

Thirty-one participants listened to the audio samples, in random order, using headphones. They rated each sample on the five perceptual scales: pleasant – unpleasant; relaxing – stressful; clean – dirty; quiet – loud; attractive – unattractive. On each scale, a higher score indicated a more positive perception of the traffic noise. When all five scales are collapsed together, as in Figure 60f, it is clear that ratings were generally highest when there were higher proportions of EVs in the traffic noise.

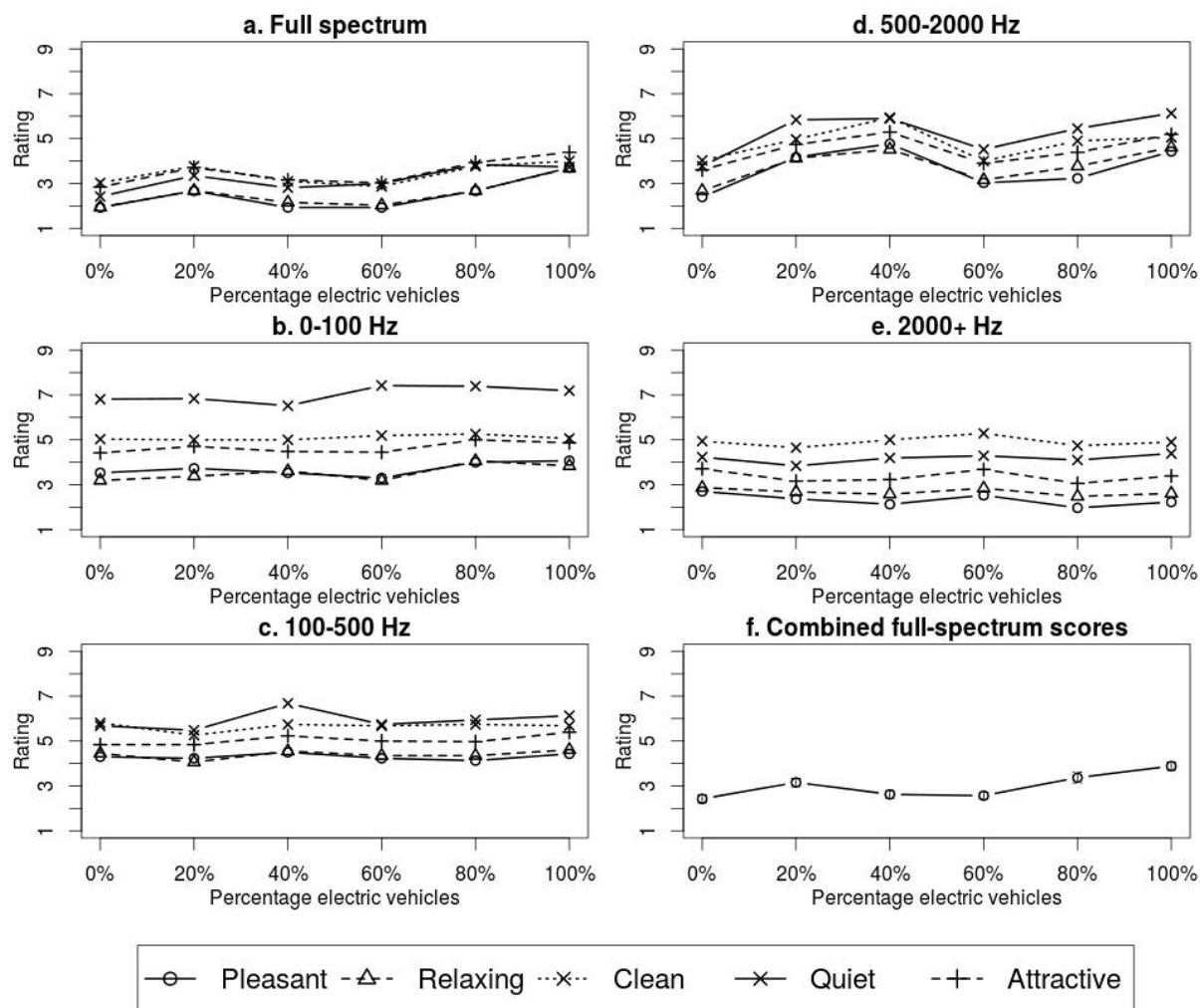


Figure 60: Subjective ratings for full-spectrum (a) and filtered (b-e) auralizations, plus combined preference ratings for the full-spectrum sounds (f), as a function of percentage of EVs in the auralization. Legend applies to a-e only; error bars in (f) represent standard errors of the mean

Participants were also tested with bandpass-filtered versions of the same sounds, to see whether any frequency components of the traffic noise were particularly associated with good or bad ratings. In Figure 61, we show the overall pleasantness ratings from the recordings that had 100% EV and 100% conventional vehicles. The first pair of columns is for the unfiltered sounds and the successive pairs are for recordings filtered with the following frequency bands: <100 Hz, 100-500 Hz, 500-2000 Hz, and >2000 Hz.

The first pair of columns in Figure 61 shows how traffic noise was rated more favourably when there were 100% EVs rather than the current situation of 100% conventional vehicles. This is a very interesting finding, as it suggests that a move to a higher proportion of EVs on national roads is likely to improve, rather than impair, the experience of people living and working nearby. The remaining columns in Figure 61 show how the preference for 100% EV mixes seems to be caused by information in the 500-2000 Hz frequency band. This is the area that contains most of the engine noise from a conventional car. As such, these data show that it is the engine of conventional cars that particularly leads to people disliking the sound of traffic on national roads when compared to EVs.

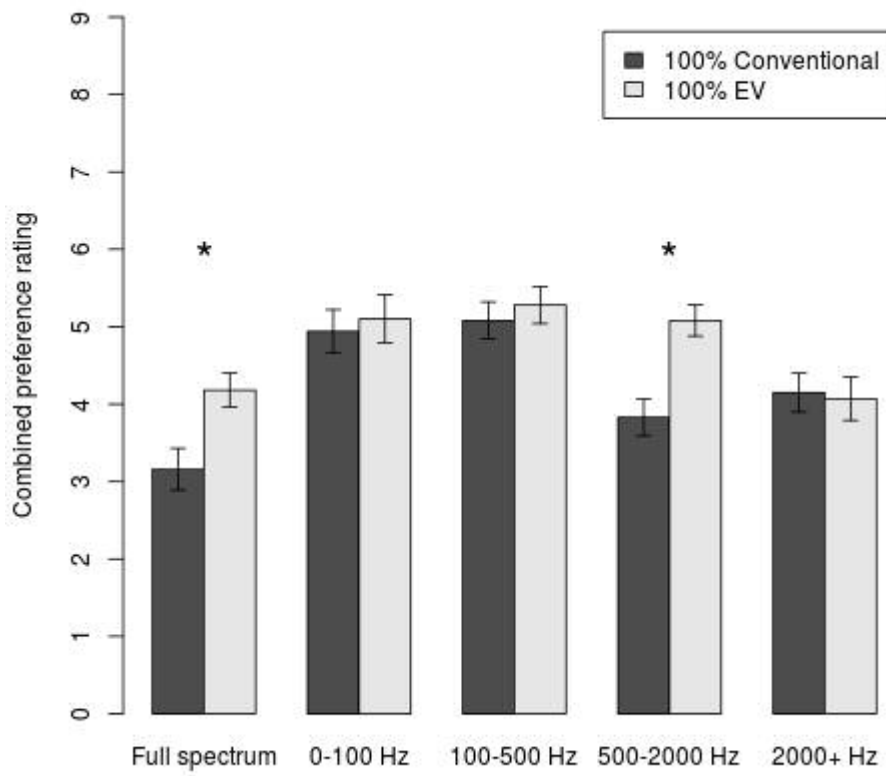


Figure 61: Mean ratings of traffic sounds for either 100% conventional vehicles or 100% electric vehicles (EV) as a function of available frequency information

## 8 Conclusions

The study undertaken in WP2 aims at characterizing and assessing the noise emitted by electric and hybrid electric vehicles, both physically by IFSTTAR and perceptually by TCD, with the final goal of evaluating in a subsequent Work Package the future impact of these vehicles on national roads. It has first provided an overview on vehicle noise measurement methods and their application to EVs / HEVs, on models representing vehicle noise emission in several noise prediction methods, as well as on the information available in the literature on EV and HEV noise emission. Then, the noise emitted by three vehicles of various size and technology has been examined through a series of measurements performed in a wide range of real-use operating conditions. An assessment of noise emission of EVs and HEVs from light and medium heavy vehicles has been drawn up on the basis of a data set available by project partners, focusing on steady speed driving conditions, and proposals for modelling these vehicles in CNOSSOS-EU have been derived.

The survey has listed several existing measurement methods to evaluate the noise emitted by vehicles. Whatever the vehicle category, the main goal is to identify the part of sound energy coming from the powertrain and the part coming from tyre-road contact. Some standard methods can benefit from using EVs or HEVs, for instance if they intend to assess rolling noise. The relevance of ISO 362, used for type approval, to these quiet vehicles needs to be examined more deeply, considering whether current acceleration tests defined from statistics on noise, use and technical performance of conventional vehicles remain representative of annoying situations for dwellers with these quieter vehicles. For an accurate noise source analysis, microphone array methods can also be implemented. Recently, new standards have been adopted, specifically intended for quiet vehicles, to evaluate a minimum noise for the safety of the other road users.

In most recent environmental noise prediction methods, the average vehicle noise emission is represented by a propulsion noise component and a rolling noise component, sometimes split into two sub-sources located at distinct heights. Their characteristics are specified in several vehicles classes, generally according to vehicle size. CNOSSOS-EU is the European method proposed for the future noise impact studies. EVs and HEVs are not specifically described in these models, but the need for considering this vehicle type has arisen. Proposing a CNOSSOS model for these vehicles is one of the aims of this WP2.

The review of existing literature on noise emission data from EVs and HEVs points out uneven results, either concerning noise differences observed between EV/HEVs and ICE vehicles or on the actual influence of acceleration on the emitted noise. Some driving situations seem to reduce the acoustical benefit of EVs and HEVs, like deceleration in case of a strong contribution of the energy recovery system. Finally, low background noise is a key point for accurate assessment of these quiet vehicles: favourable environmental conditions may be difficult to fulfill on common test sites.

Three vehicles have been used in this Work Package to perform trials at pass-by on a test site, under various real-use operating conditions (constant speed, moderate or full acceleration, deceleration and braking): a small electric passenger car, a larger hybrid passenger car and an electric truck. The issue of background noise happened to be critical at low speed for the vehicles in the electric mode in some frequency bands and the introduction of some correction terms has been proposed. The presence of a direct transmission or an automatic gearbox hampers the separation of powertrain noise from rolling noise through common pass-by test procedures: the addition of simultaneous on-board instrumentation and/or indoor tests could help to refine the analysis. Under electric mode the global noise

levels rise linearly with  $\log(\text{speed})$  for all vehicles: doubling speed increases the emitted noise by 9 to 12 dB(A). Acceleration but also braking situations produce a significant raise of noise emission, the influence of the energy recovery is suspected in the latter case. For the hybrid vehicle the noise level difference is about 4 dB(A) between the electric and hybrid modes at the constant speed of 20 km/h. There is no more difference above 40 km/h. The overall trends observed with these measurements confirm information available in the literature. In addition, it provides detailed trends in frequency, as well as investigations on deceleration and braking situations, which are not usually considered in vehicle noise emission but come out to be of particular interest on EVs and HEVs using energy recovery. The impacts of the different operating conditions on the vehicle noise emission have been quantified in this study.

The noise data available from measurement by partners on EVs and HEVs have been collected and analysed. Concerning light electric vehicles (including also hybrid vehicles in electric mode), the linear increasing trend of the global noise with  $\log(\text{speed})$  is confirmed. This may differ in some frequency bands. At any speed in the range 20-50 km/h, the global noise difference between the quietest and the noisiest car is 4.5 dB(A). CNOSSOS-EU clearly overestimates these vehicles and a corrected version is required for EVs. Concerning light hybrid vehicles, the sample group of vehicles is small and comments are only indicative. CNOSSOS-EU tends to overestimate the emitted noise at low speed, mainly at high frequencies. As for medium heavy vehicles, the emitted noise levels when operated in electric mode vary notably with the vehicle size (GVW and tyre size). When in hybrid mode, the hybridization mode might be a key parameter for the vehicle performance concerning noise. The inadequacy of CNOSSOS-EU for the vehicles in these categories has been underlined. The predominance of the propulsion noise over the whole speed range for vehicles of category 2 in CNOSSOS-EU does not agree with the IFSTTAR authors' experience. This issue has been deepened on the basis of existing data on ICE vehicles in this category, available by IFSTTAR and in the published literature. The discrepancies observed between these ICE data and CNOSSOS-EU requires further investigation with current medium heavy vehicle fleets in circulation on various roads. Any proposal for a correction of CNOSSOS-EU for medium heavy EVs and HEVs would only subsequently make sense.

Finally, a proposal has been formulated for taking account of electric vehicles in CNOSSOS-EU for vehicle category 1 (light vehicles). The approach is based on constant correction terms to be applied on the propulsion noise component given in CNOSSOS-EU for ICE cars, as long as another mathematical equation, physically consistent with the actual propulsion noise from electric vehicles, is not available. The values of these correction terms have been determined and are given in each octave band from 125 Hz to 4000 Hz. Until the conclusions on rolling noise are drawn from WP3 of FOREVER, the rolling noise currently validated for light vehicles in CNOSSOS-EU is used. In global levels, the weight of the propulsion noise component in the total noise from EVs remains small (if not negligible) in the total noise, which is not systematically true in some octave bands. For light hybrid vehicles operating in hybrid mode, no correction is necessary and CNOSSOS-EU specifications are recommended. When operated in electric mode, hybrid vehicles behave like full-electric vehicles. *Since the number of vehicles available in the analysis was limited, the results given in this report should be taken as indicative and values provided represent a first step toward the specification of electric vehicles in CNOSSOS-EU. Confirmation by complementary studies is necessary.*

The work conducted by TCD has demonstrated the potential for industry standard pass-by data to generate realistic auralizations of road traffic environments with various vehicle mixes. This is useful tool for many stakeholders wishing to judge community responses to a

change in the road traffic make up. Auralizations are inherently easier to understand and communicate than dB levels as the audience can experience for themselves the acoustic environment beside a national route way. The University of Bath have demonstrated that these auralizations can be used effectively to measure a change in the perception of human listeners to the noise.

The road environments which were tested in FOREVER were confined to vehicle types representative of the commercial consumer market for EVs, i.e. the family car. It is easily possible to extend this work to include heavy goods vehicles and non-traditional vehicle designs on national route ways. This work was beyond the scope of the FOREVER project. FOREVER has successfully developed and deployed tools which have demonstrated clear results for assessing a change in community response to noise exposure. Although this was a small element of the overall project the results show that a transition to greater percentage of EVs in the traffic mix will not harm and will likely improve the community response to noise exposure.



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## Acknowledgement

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## Appendix A: Noise emission of the electric passenger car under acceleration, deceleration and braking, in octave bands

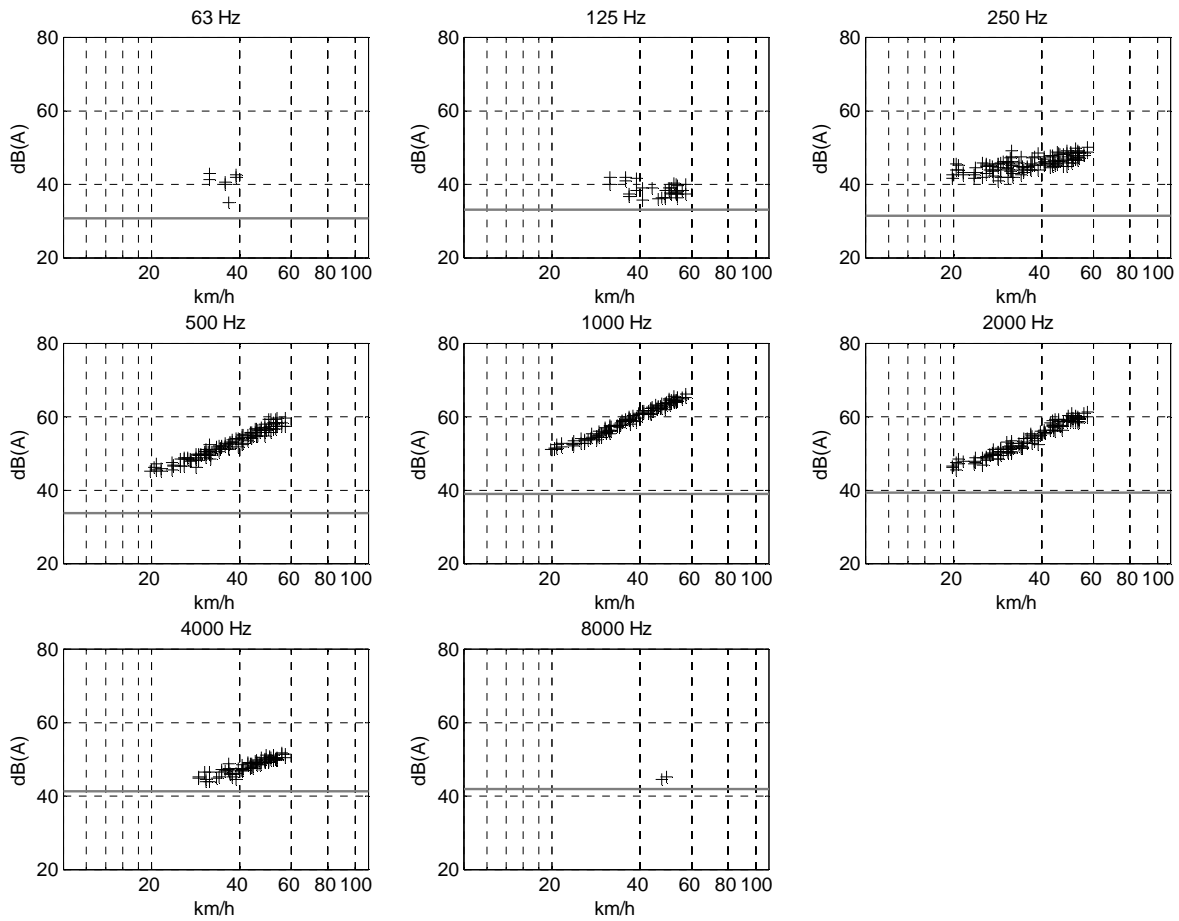


Figure A1: Distribution of the maximum sound pressure level in dB(A) in octave bands for the Citroen C-Zero under moderate acceleration, at 7.5 m from the track centre



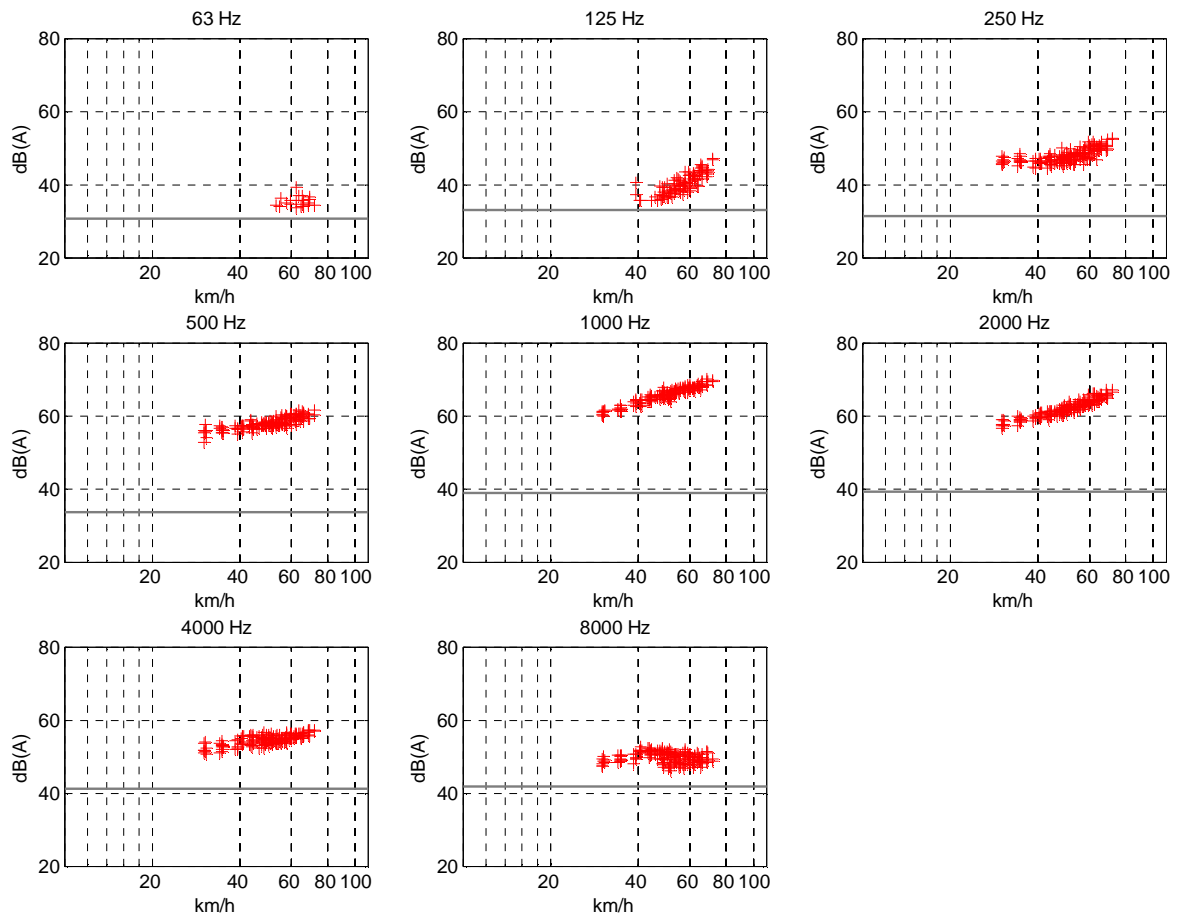


Figure A2: Distribution of the maximum sound pressure level in dB(A) in octave bands for the Citroen C-Zero under full acceleration, at 7.5 m from the track centre

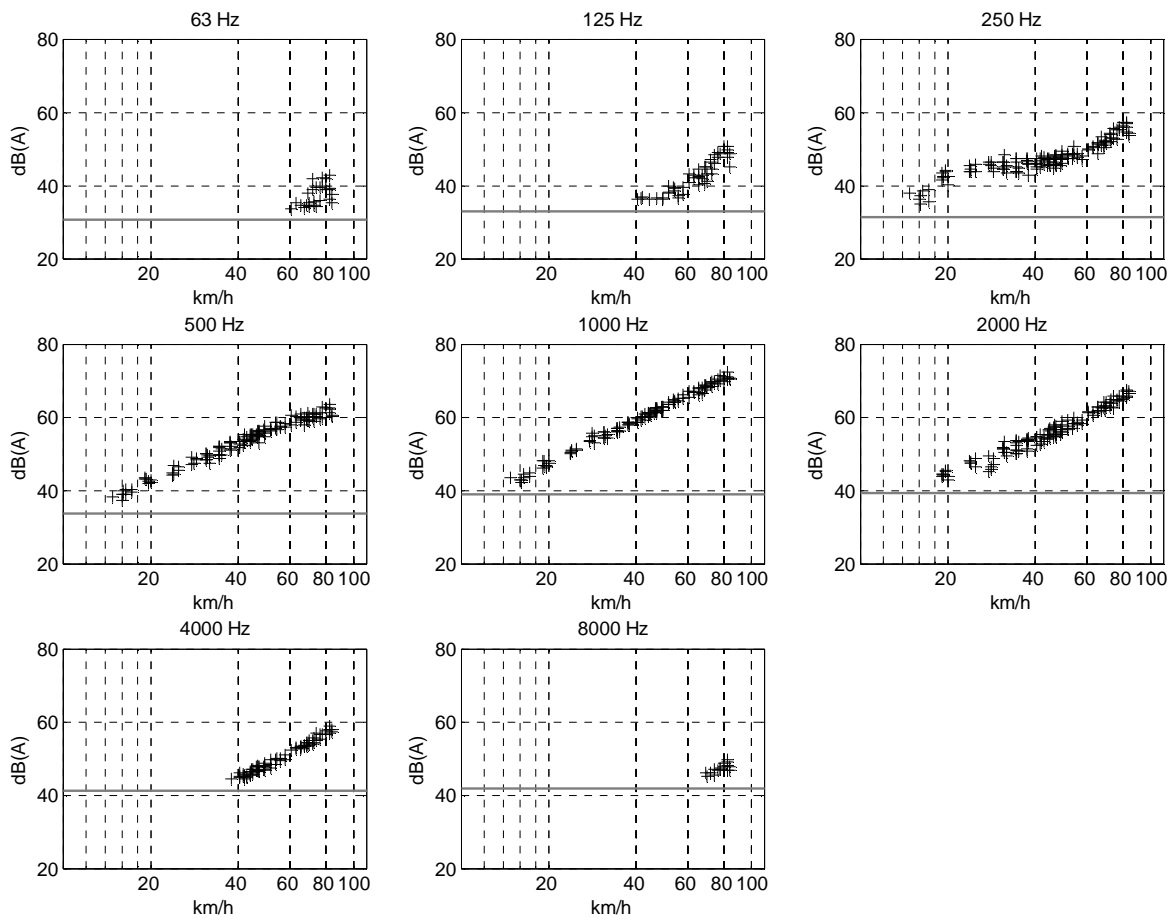


Figure A3: Distribution of the maximum sound pressure level in dB(A) in octave bands for the Citroen C-Zero under deceleration (without braking), at 7.5 m from the track centre

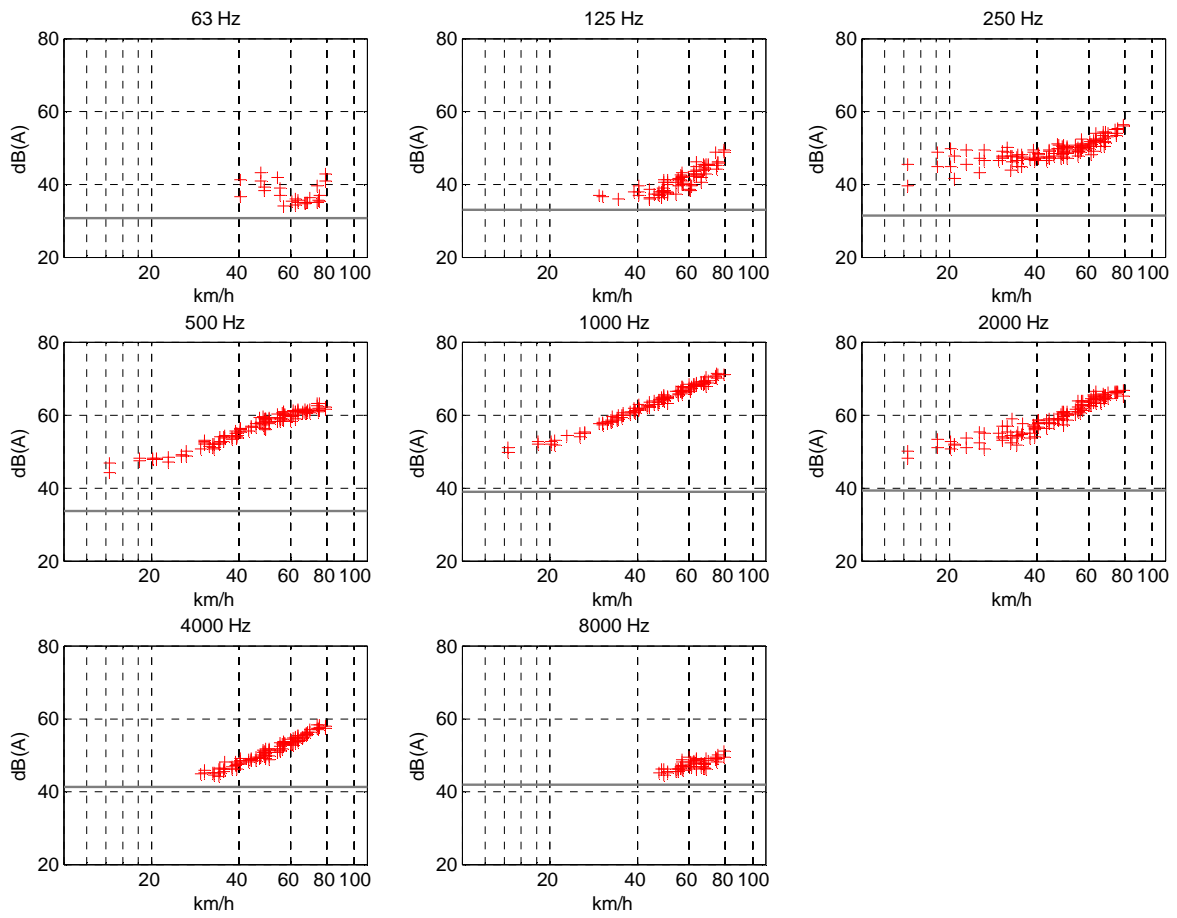


Figure A4: Distribution of the maximum sound pressure level in dB(A) in octave bands for the Citroen C-Zero under braking, at 7.5 m from the track centre

## Appendix B: Noise emission of the hybrid passenger car at constant speed in octave bands

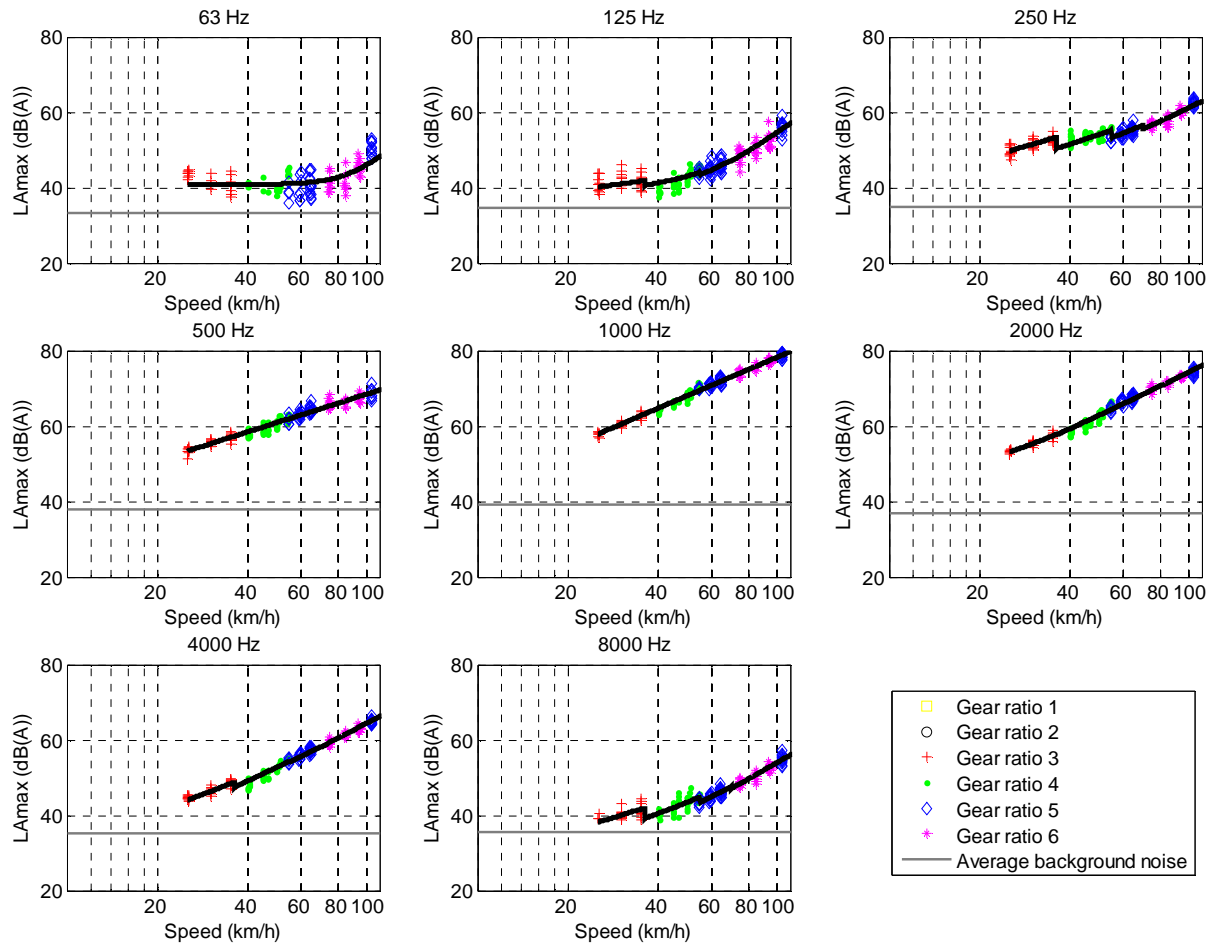


Figure B5: Distribution of the maximum sound pressure level in dB(A) in octave bands for the overall HEV in mode Hybrid1 at constant speed, for the various gear ratios, at 7.5 m from the track centre

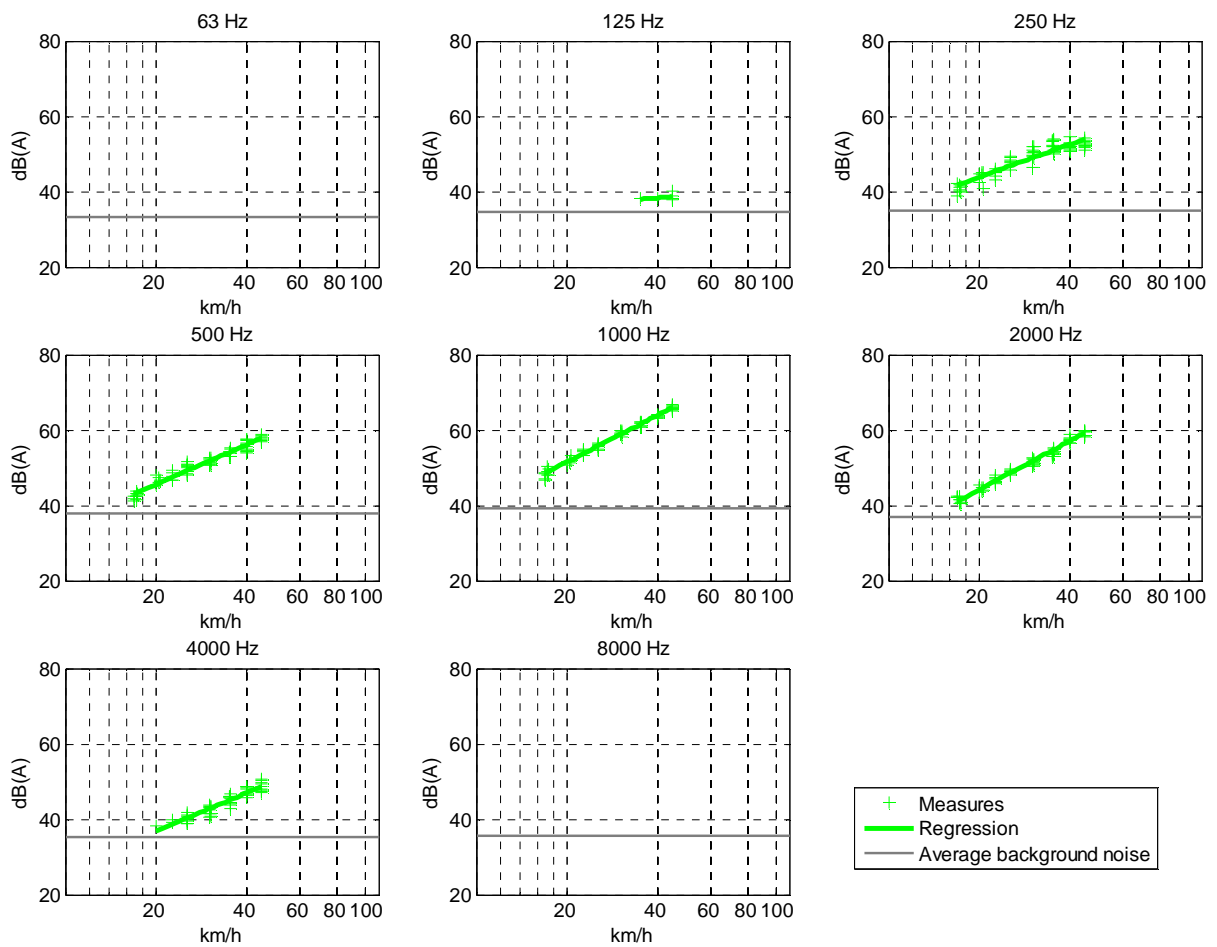


Figure B6: Distribution of the maximum sound pressure level in dB(A) in octave bands for the overall HEV in electric mode at constant speed, at 7.5 m from the track centre

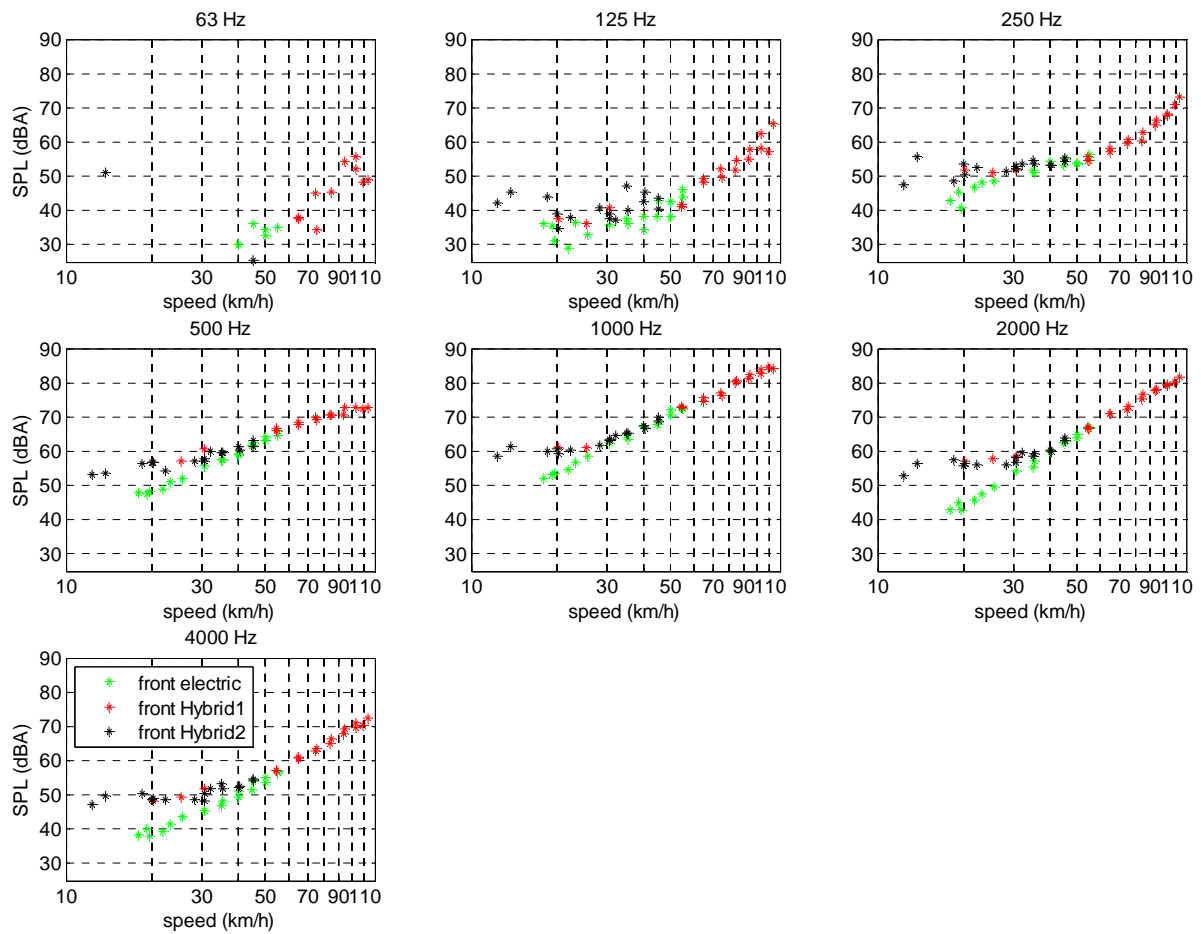


Figure B7 : Contribution of the front axle source area of the HEV in each octave band at constant speed – Sound pressure levels at the reference distance 2.7 m

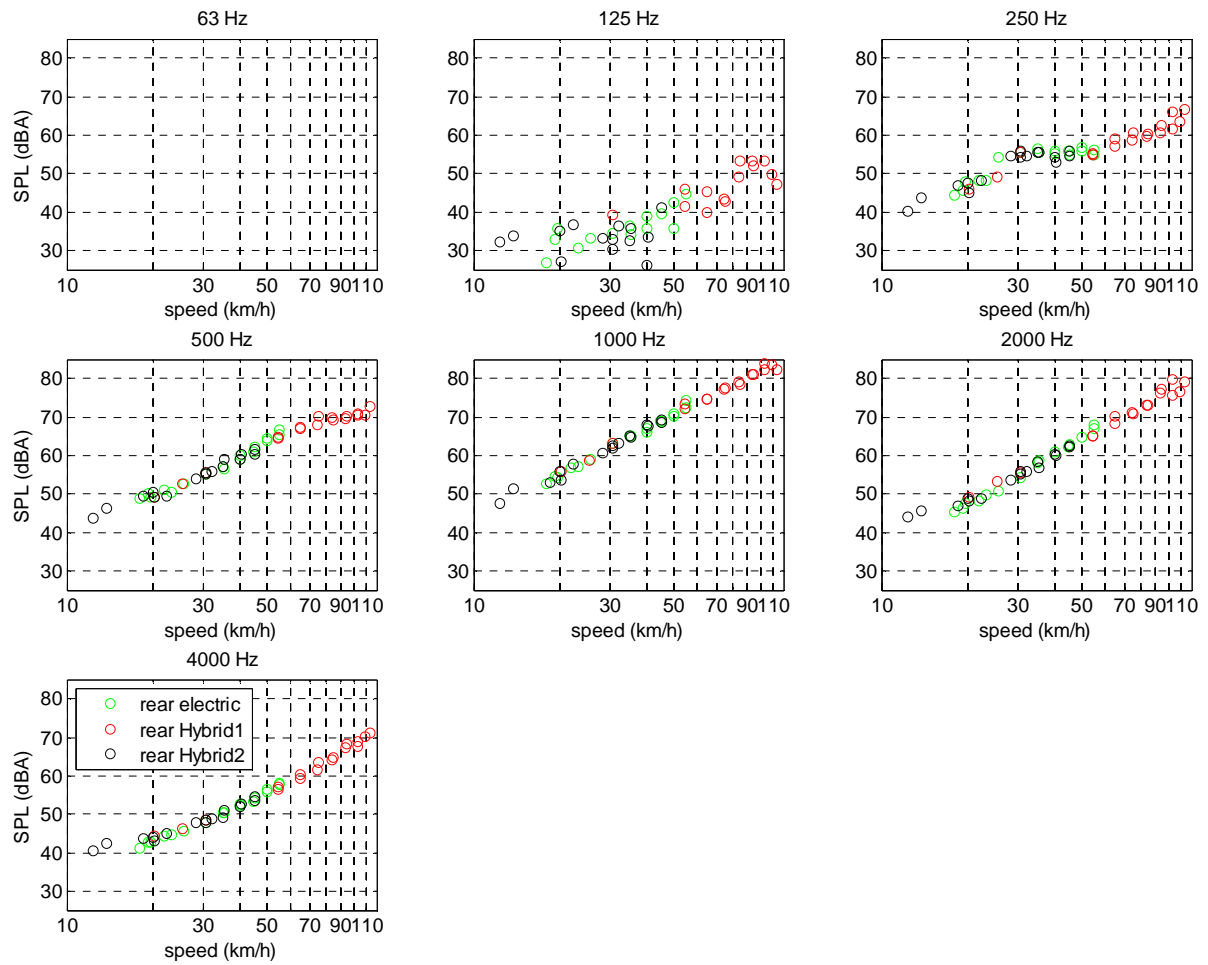


Figure B8: Contribution of the rear axle source area of the HEV in each octave band at constant speed – Sound pressure levels at the reference distance 2.7 m

## Appendix C: Noise emission of the electric truck at constant speed, under acceleration and deceleration in octave bands

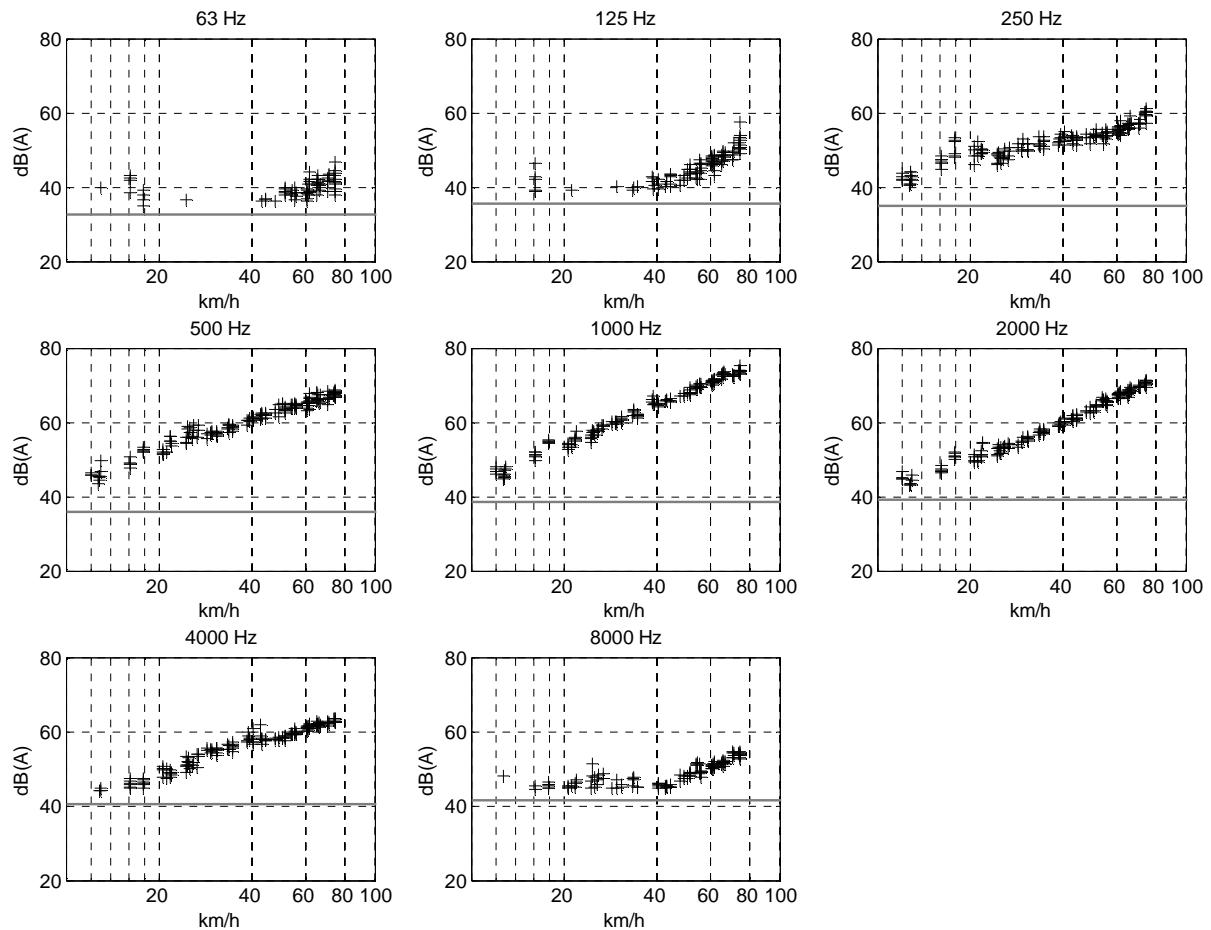


Figure C9: Distribution of the maximum sound pressure level in dB(A) in octave bands for the electric truck (cat. N2) at constant speed, at 7.5 m from the track centre



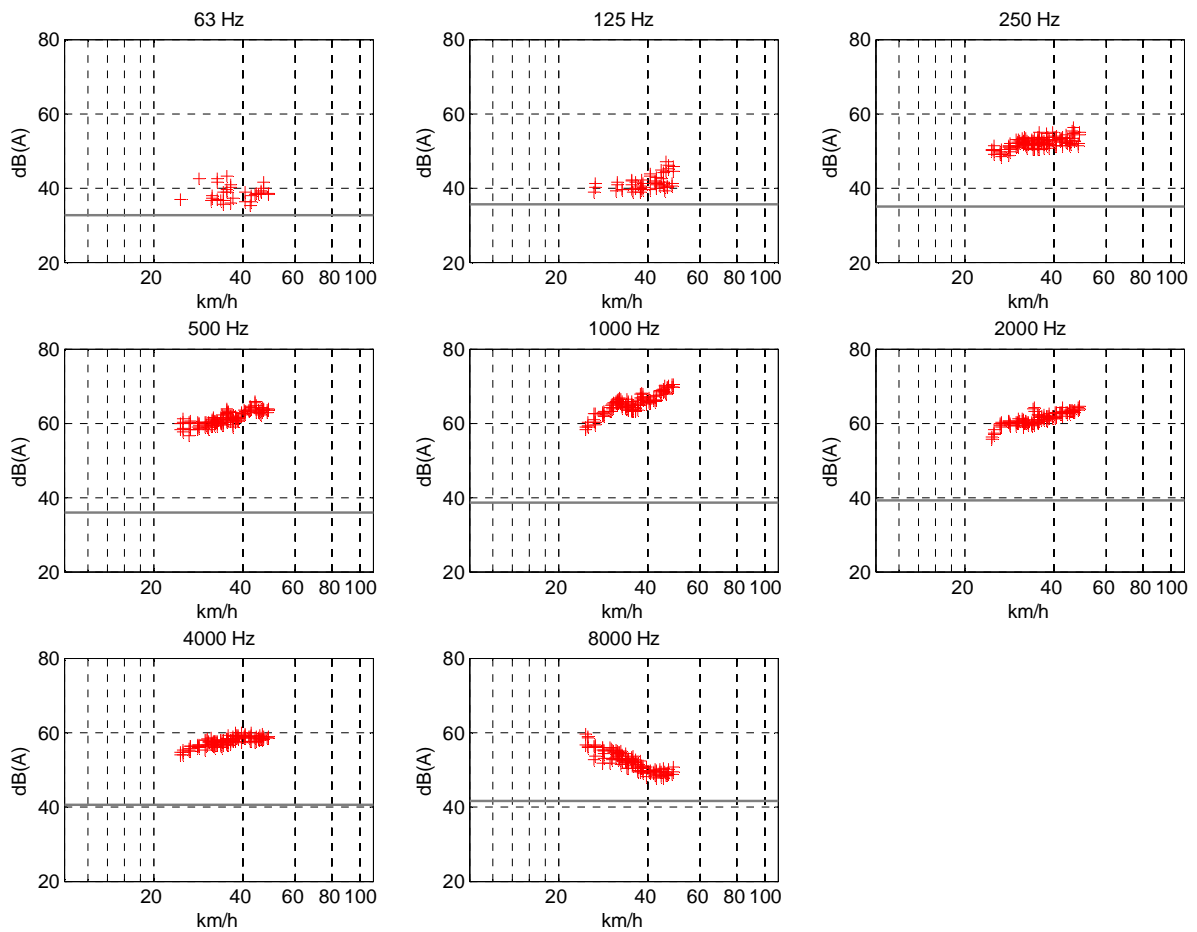


Figure C10: Distribution of the maximum sound pressure level in dB(A) in octave bands for the electric truck (Cat. N2) under acceleration, at 7.5 m from the track centre

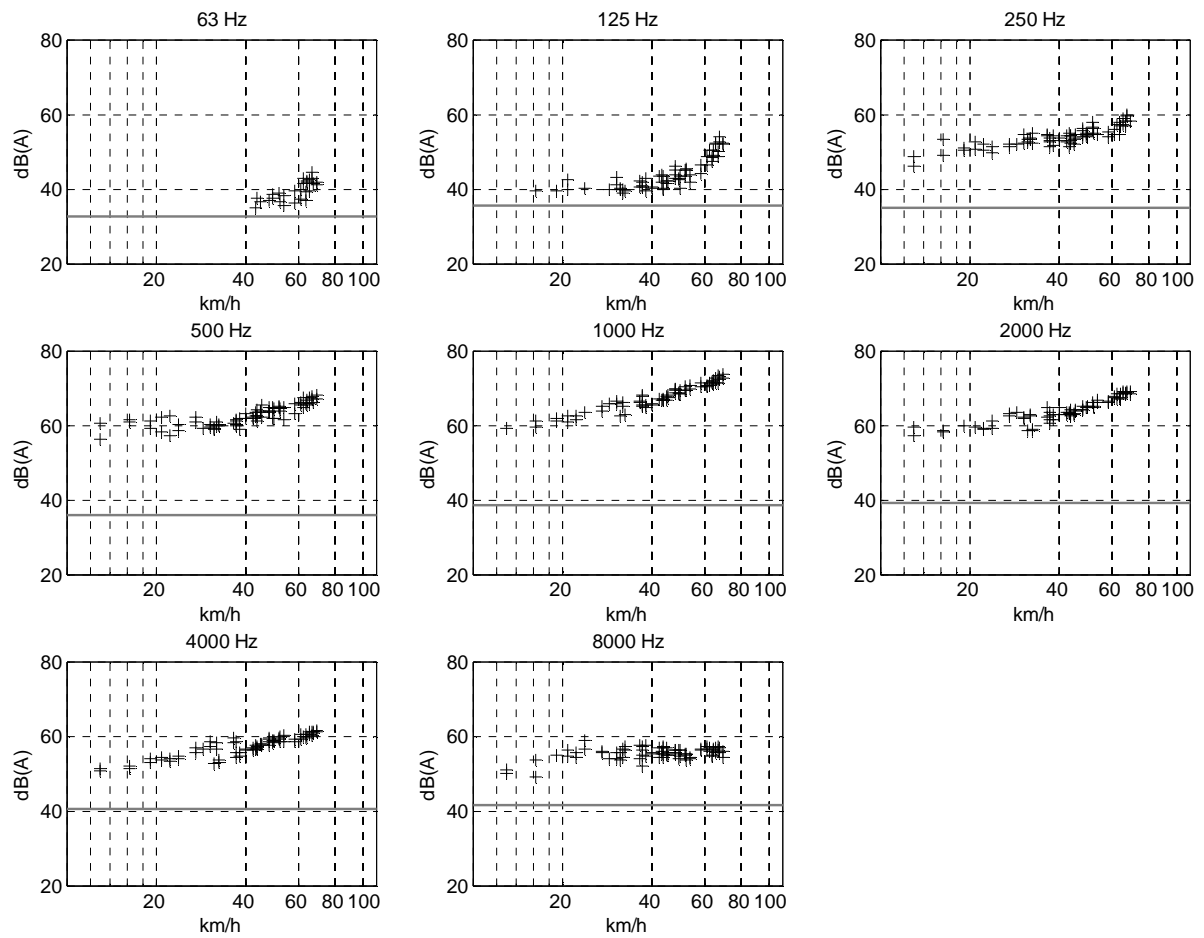


Figure C11: Distribution of the maximum sound pressure level in dB(A) in octave bands for the electric truck (Cat. N2) under deceleration, at 7.5 m from the track centre

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## Appendix D: Figures in octave bands for the adaptation of CNOSSOS to EVs and HEVs

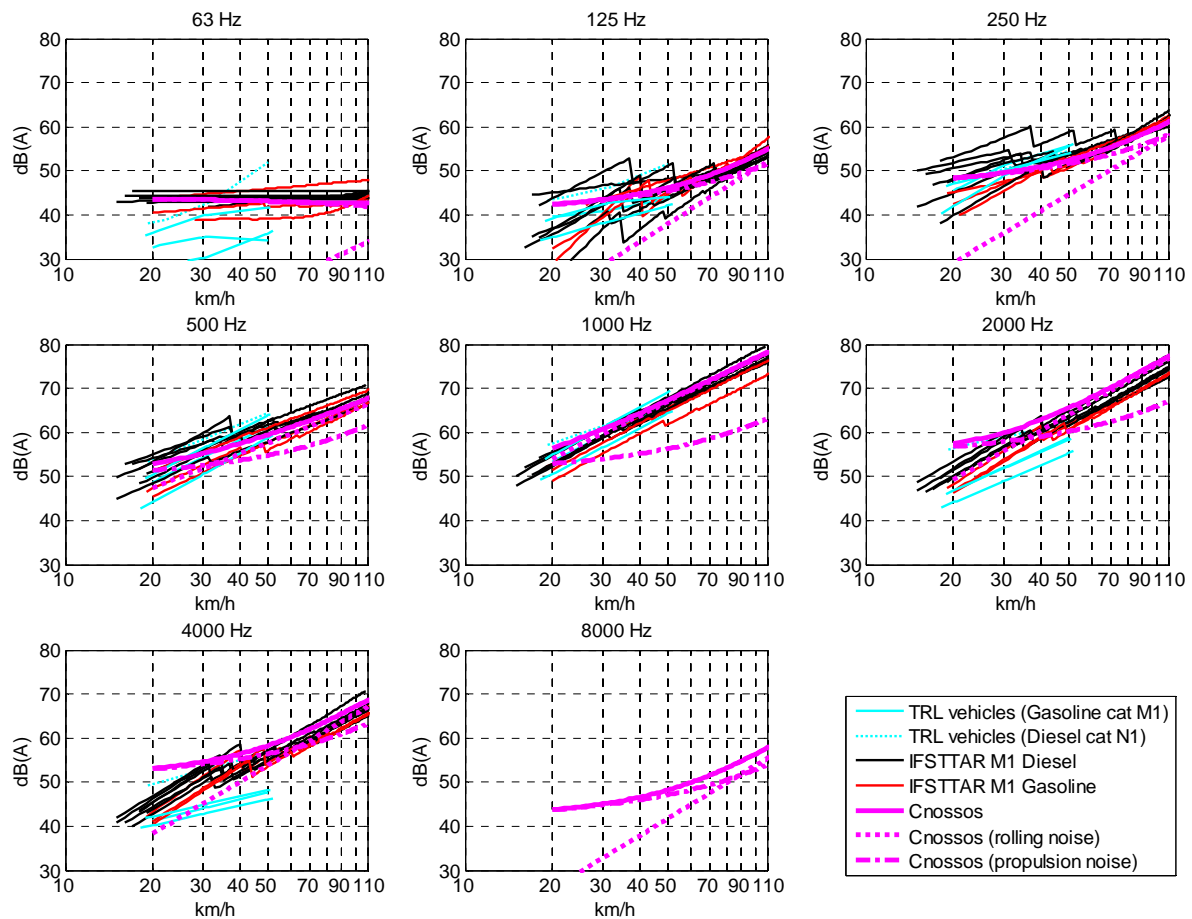


Figure D12: Distribution of the maximum sound pressure level in dB(A) in octave bands for the ICE vehicles at steady speed and CNOSSOS-EU, at 7.5 m from the track centre – IFSTTAR Diesel (black), IFSTTAR Gasoline (red), TRL (blue)

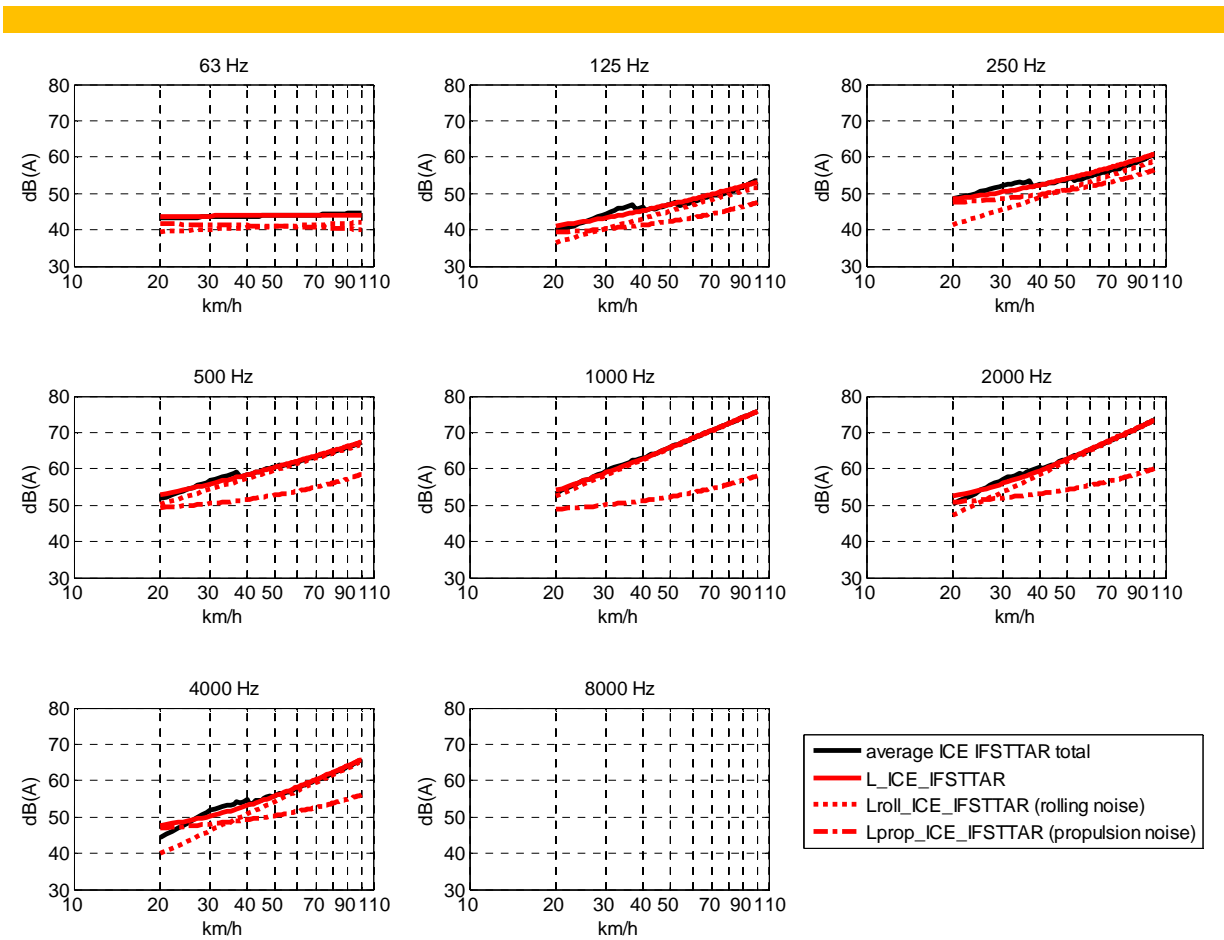


Figure D13: Identification of the propulsion noise component and the rolling noise component for the average of the ICE cars – maximum sound pressure level at 7.5 m

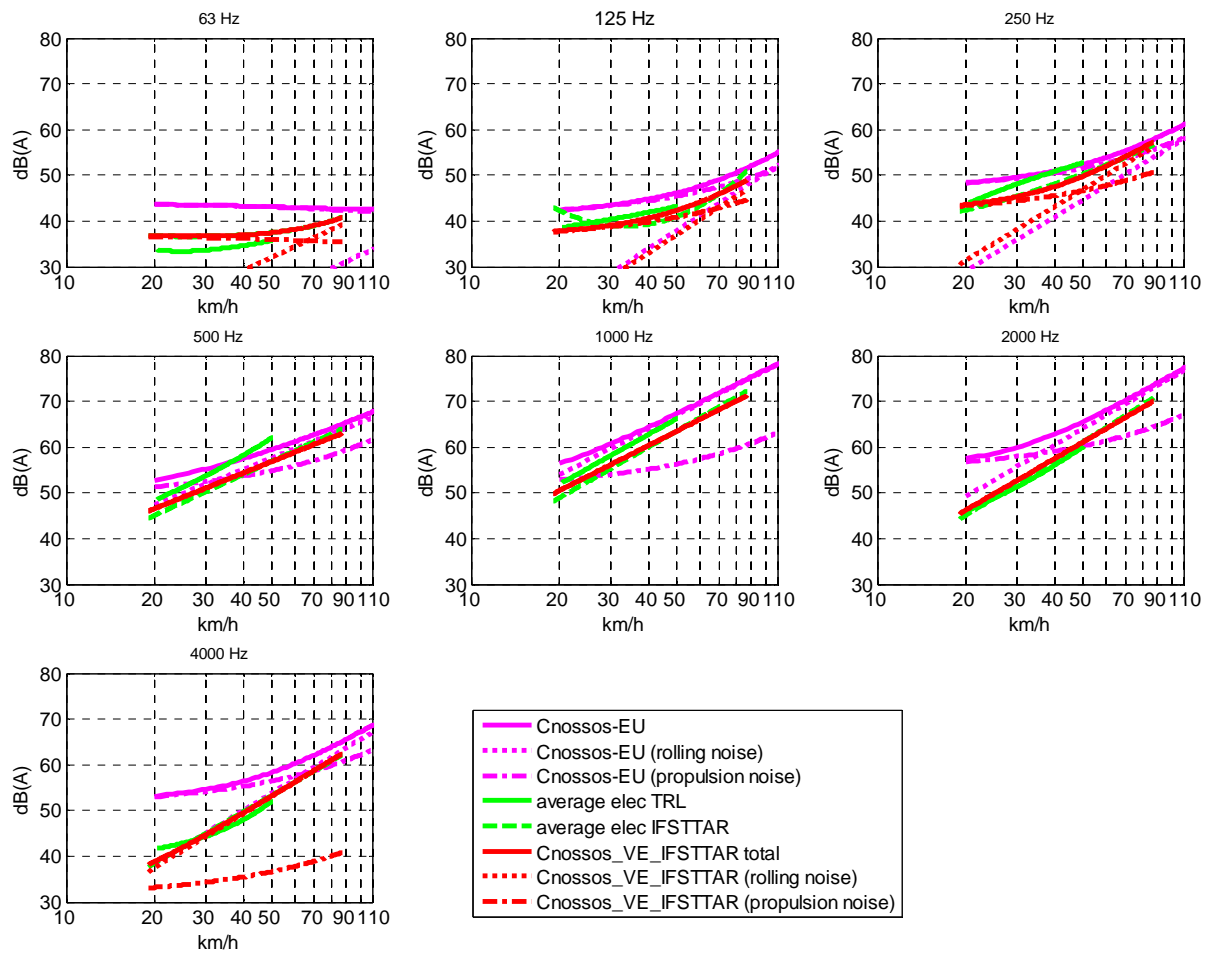


Figure D14: Identification of the propulsion noise component and the rolling noise component for the average of the VE cars, using the approach Test 1 – maximum sound pressure level at 7.5 m

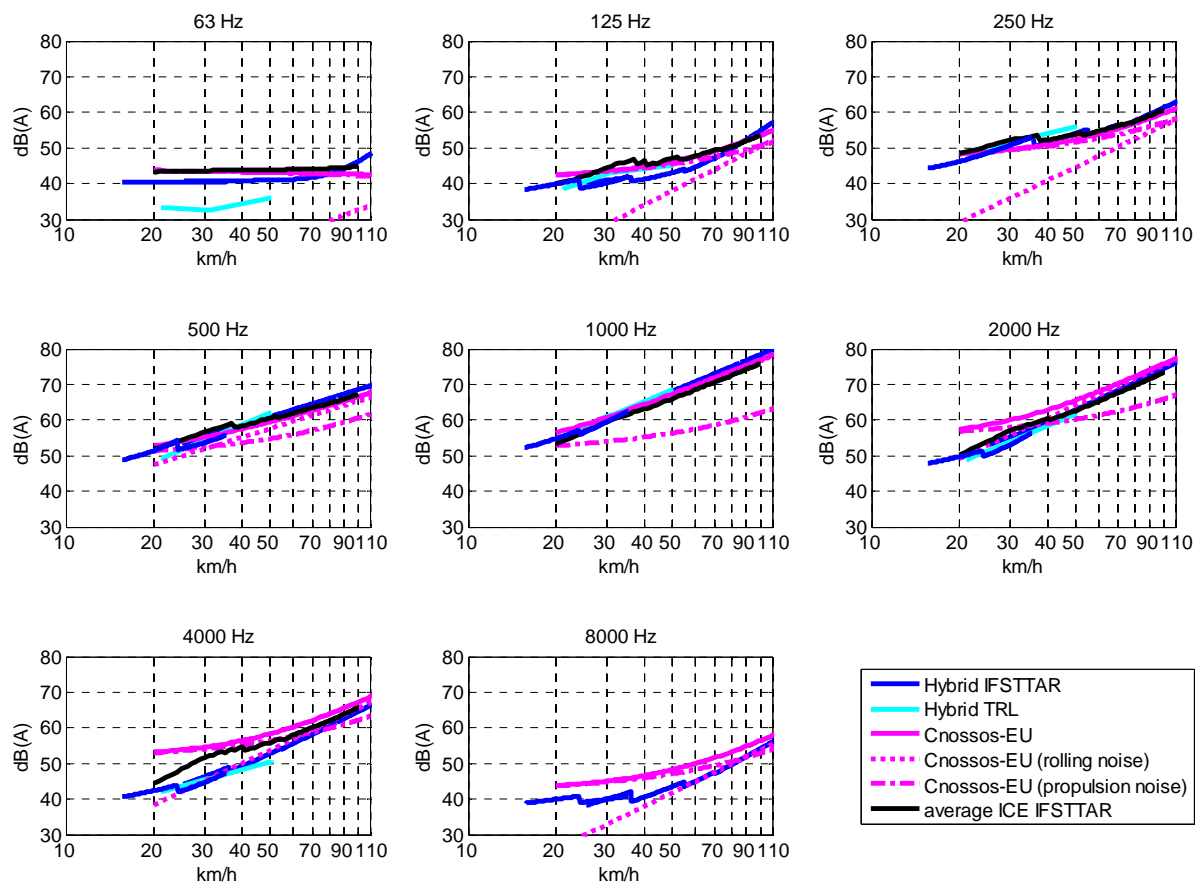


Figure D15: Distribution of the maximum sound pressure level in dB(A) in octave bands for the average ICE car, the hybrid vehicles and CNOSSOS-EU, at 7.5 m from the track centre, at steady speed – Average IFSTTAR ICE car (black), IFSTTAR hybrid cars (dark blue), TRL hybrid car (light blue), CNOSSOS-EU (purple)