CHALMERS
UNIVERSITY OF TECHNOLOGY

Evaluation of noise emission from passenger cars in urban traffic

A comparison between electric passenger cars and passenger cars with internal combustion engines

Master's thesis in Master Program Sound and vibration

FILIP WADMAN

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's thesis ACEX30
Gothenburg, Sweden 2023

Master's thesis ACEX30

Evaluation of noise emission from passenger cars in urban traffic

A comparison between electric passenger cars and passenger cars with internal combustion engines

FILIP WADMAN

Department of Architecture and Civil Engineering
Division of Applied Acoustics
Chalmers University of Technology
Gothenburg, Sweden 2023

Evaluation of noise emission from passenger cars in urban traffic
A comparison between electric passenger cars and passenger cars with internal combustion engines

FILIP WADMAN

Supervisor: Senior advisor Sigmund Olafsen Brekke & Strand Akustik
Examiner: Professor Jens Forssén, Department of Architecture and Civil Engineering

Department of Architecture and Civil Engineering
Division of Applied Acoustics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Picture taken during the measurement.

Department of Architecture and Civil Engineering
Gothenburg, Sweden 2023

Evaluation of noise emission from passenger cars in urban traffic
A comparison between electric passenger cars and passenger cars with internal combustion engines
Filip Wadman
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

Electric vehicles (EV) are becoming a larger part of the traffic flow present in the traffic today. The noise emission from cars driving at higher speed is dominated by the noise of the tyres and the contact with the road. The noise from the engine becomes more dominating at the lower speeds, thus one can start to think how this could make the emitted noise deviate between electric cars and cars with traditional combustion engines. If EVs in the future would contribute to a larger part of the total traffic flow, which is not unlikely, one could question if the traffic noise within densely populated areas would decrease for the roads with lower speed limits. The aim of the project is to investigate if there is a difference between the traffic noise emitted by electric cars compared to internal combustion engine vehicles (ICEV) and if so to what extend.

To investigate this, measurements of single vehicles were made at roads with speed limits between 15 km/h and 60 km/h. The sound exposure level (SEL), maximum sound pressure level (SPL), equivalent SPL, sound power level and psychoacoustic annoyance (PA) were analyzed together with a listening test where participants rated the annoyance for both vehicle types for the different speed limits. The results showed that EVs were only a few decibel lower regarding the SEL and maximum SPL and the sound power levels were almost equal. The small deviations could be seen to fall within the uncertainty based upon the calculated confidence interval (CI). From the listening test it was seen that participants rated the annoyance from the different vehicle types equally and EVs were not perceived as less annoying. It could therefor not be concluded fully from the measurement and listening test that EVs were quieter than ICEVs.

Keywords: Electric vehicles, Noise emission, Urban traffic, Passenger cars, Internal combustion engines, Sound exposure level, Psychoacoustic, CNOSSOS.

Acknowledgements

This work will mark the end of my five years of studies at Chalmers University of Technology and especially my last two years spent at the Division of Applied Acoustics. Even thought it marks an end of a period full of tough studies, fun experiences and many new friends it is also the beginning of a new chapter to be written. I would like to thank all of my friends which I have met at the department and during my bachelor year for encouraging discussions and shared knowledge. In addition I would like to express my gratitude towards the whole staff at the Division of Applied Acoustics for the knowledge I have learned throughout the last two years. The listening test was enabled by resources funded by the HEAD Genuit Foundation under the agreement P-22/01-W.

I would like to express my full gratitude to my supervisor Sigmund Olafsen at Brekke & Strand Akustikk. Your knowledge and support from the start of the work have been highly appreciated. To always have the feeling of your support and friendship at any time has inspired myself to one day be able to be in your position and guide new acousticians. In addition I would like to express my full gratitude to my examiner Jens Forssén who has helped me during the whole work and supported me with valuable knowledge to finish my master thesis. At last but not least I would like to express my warmest gratitude to my family which has always been there for me.

Filip Wadman, Gothenburg, June 2023

Contents

List of Figures

List of Tables

1

Introduction

This section will explain the background of the master thesis, why the chosen subject affects an existing problem and why it is an important subject to study. The aim of the master thesis will be defined together with objectives that should be investigated to answer the aim of the master thesis. In addition the limitations will be discussed and if there is any social, ethical and ecological aspects that needs to be regarded.

1.1 Background

An unwanted sound is referred to as noise. Therefor noise can can be everything from a neighbour drilling in the wall to a common blackbird singing in the tree depending on the person. Environmental noise where traffic noise is included is a significant risk for the human health which concern both the general public and the governing politician. The exposure of traffic noise either from high noise levels or during long time can lead to sleep disturbance, hearing impairment, tinnitus, cognitive impairment and cardiovascular diseases. Traffic noise can originate from cars, trains and airplanes for example. Some countries in Europe like France, Germany and the United Kingdom arrange national surveys regarding which different noises that is disturbing people the most. Noise from road traffic are rated to be the most annoying noise in these widely spread surveys [1]. Therefor one can understand how important it is to have knowledge about how to reduce the traffic noise and particularly the road traffic noise in the future. This would help increase the human health and save lives.

Many parameters influences the result when measuring the noise from road traffic such as the road surface, type of tyre, aerodynamics and the propulsion noise which strongly correlates with the model of the car which means if it is an EV, hybrid electric vehicle (HEV) or an ICEV. The propulsion noise dominates at the lower speeds for the vehicles whereas the noise from the tyre and road surface, normally referred to as tyre/road noise, dominates when reaching higher speed limits. For EVs the propulsion noise is much lower compared to vehicles with internal combustion engines at lower speeds [2]. Consequently the urban traffic noise levels could be influenced and potentially reduced in the future if a larger part if the vehicles becomes EVs. The noise abatement that could be gained would mainly regard the traffic noise where the propulsion noise dominates.

EVs has between 2010 and 2017 gained a momentum and increased both in popularity and market shares throughout Europe [3]. The growing share of EVs and its possible benefits regarding noise abatement in the future is still to be explored further. It is mainly a reduction of traffic noise for the lower speed limit which is expected because of the deviation in propulsion noise. There have been studies evaluating up to which speed the propulsion noise dominates and how much the difference is between EVs and internal ICEVs [4][5]. It is often one or two different vehicles that are being compared and at most a couple, thus is is hard to evaluate how this could be interpreted for the broader perspective of traffic noise in lower speed limits. More research and measurements needs to be collected to verify and see if there is a possible benefit of EVs.

This master thesis have been made in collaboration with Brekke & Strand Akustik which have been working with evaluating the objective and subjective assessment of noise from road traffic noise during a longer period. Earlier work have been made regarding the evaluation of noise from the tram in Oslo [6] together with collaborations in a number of master thesis evaluating the noise from electrical vehicles [7] and the psychoacoustical characteristics of tram noise [8] to mention a few. This work will hopefully contribute to collect a broader perspective from both objective measurement and subjective perception in a listening test within the area of road traffic noise originating from EV and ICEV.

1.2 Aim

The aim of the master thesis is to investigate if there is a difference between the noise emitted by EVs compared to ICEVs. The thesis aims to implement this investigation at vehicles classified as light motor vehicles and in low speed which is defined to be up to 60 km/h. The aim is to collect data for a larger set of vehicle representing the average seen at the roads rather then in laboratory environment.

1.3 Objectives

To easier investigate the aim it has been divided into a subsection of questions which are:

- How does the values for L_{AE}, L_{Amax} and L_{WA} deviate for the different vehicle types including the frequency spectra?
- Is there and if so for which speed limits is there a difference between the vehicle types?
- Is there other parameters not disclosed by the measured values that influences the perceived sound of the different vehicle types?

1.4 Limitations

This report will focus on evaluating the difference between EVs and ICEVs. To specify it further only light motor vehicles will be evaluated which includes passengers cars and delivery vans under 3,5 tons classified as Category 1 in CNOSSOS-EU [9]. Furthermore as stated earlier speed limits up to 60 km/h will be evaluated which means that the area of focus will be to investigate how the deviation of propulsion noise affect the noise emission from light motor vehicles of different categories.

1.5 Social, ethical and ecological aspects

The outcome of this report is to develop more knowledge about how the noise emission between EVs and ICEVs differs. This could in the long run affect the environmental noise in the society which influences the human health. The social aspects of the outcome in this report are present but is not supposed to be investigated. An ecological aspect is how the emission from the transport section could change if EVs would increase and reduce the fossil-fueled vehicles in the future. Both of this aspects are relevant but is not within the scope of this report to answer. Therefor they will not be evaluated. During the listening test it is of importance that the participants integrity is kept which is an ethical aspect.

2

Theory

The underlying theory and concepts touched upon within the report are presented below. Firstly the different sound metrics coupled to the report are presented to be followed by the physics of the generation of road traffic noise. The calculation method used to calculate values to compare with the objective measured values is brought up after. Psychoacoustic and its belonging parameters loudness, sharpness, roughness, fluctuation strength and tonality is lastly introduced to the reader.

2.1 Sound

2.1.1 Sound pressure level

The most common measure of sound is the SPL. The range of the sensitivity of the human ear is extremely large. The lowest pressure variations the human ear can notice is of $2 \cdot 10^{-5}$ Pa, also referred to as the threshold of hearing. In the other end of the range, the maximum pressure variations the human ear can notice before it starts taking damage is 20 Pa, referred to as the threshold of pain. Therefor a logarithmic scale is used when calculating the SPL which leads to manageable numerical values and the logarithmic metric decibel (dB) is used [10]. The SPL is given by equation 2.1:

$$L_p = 10 \cdot \log_{10}(\frac{p^2}{p_{ref}^2})(dB) \tag{2.1}$$

where p_{ref} is the reference value of $2 \cdot 10^{-5}$ Pa and p is the acoustic pressure in pascal.

2.1.2 Equivalent sound pressure level

To express a sound which has a time varying sound level over a longer period the equivalent SPL, L_{eq}, can be used. The equivalent SPL can be used when for example measuring the noise from a road over a longer period [11]. It is given by equation 2.2:

$$L_{eq} = 10 \cdot \log_{10}(\frac{1}{T}\int_0^T 10^{\frac{L_p}{10}} dt) \tag{2.2}$$

where T is the time period of the recorded measurement in seconds.

2.1.3 Sound exposure level

SEL denoted L_E is a measure of the acoustic energy of a sound normalized to the reference duration of one second. Both the duration of the sound and the perceived level is taken into account when calculating the SEL. This enables the benefit to compare noises of different duration to each other. The SEL is calculated by Equation 2.3 and is often used when measuring pass-by events of single vehicles.

$$L_E = 10 \cdot \log_{10} \frac{1}{t_0} \int_{t_1}^{t_2} \frac{p^2(t)}{{p_{ref}}^2} dt \, (dB) \tag{2.3}$$

here t_0 is the reference duration of 1 s, t_1 and t_2 are the time interval for the sound containing all the significant sound energy of the sound.

2.1.4 Sound power level

The sound power is the sound energy emitted from an objective per unit time. It is independent of its acoustical environment which makes it a usable unit when comparing objectives. The sound power level in for this report is derived from the measured L_{Eq} given by equation 2.4 and where the constant plus six originates from the amplification of pressure doubling when measuring over hard ground and the source is place close to the ground [12].

$$L_{eq} = L_W - 10 \cdot \log_{10}(4LUT) + 6 \tag{2.4}$$

here L is the shortest distance from the source to the receiver, U is the speed of the vehicle in m/s and T is the integration time of the equivalent level.

2.1.5 Frequency

Periodic sound waves travelling in a medium will oscillate, the number of wave cycles that occur during the time period of one second defines the frequency. The frequency is given by the relation between the speed of sound, c, and the wavelength, λ, where the wavelength of a sound is the length of one complete cycle. The unit of frequency is hertz (Hz) and the frequency is given by equation 2.5:

$$f = \frac{c}{\lambda} \, (Hz) \tag{2.5}$$

2.1.6 A-weighting

The sensitivity of the human ear deviates for the frequencies composed in a sound, thus a weighting filter is applied to better reflect how humans perceive the sound. There are different weighting filters that are used representing the human ears frequency dependence in different sound pressure ranges. The most used weighting filter is called A-weighting and the measured levels used with such a filter are called weighted levels [11]. The A-weighting curve used for sound level meters are defined in the international standard IEC 61672-1:2013 and is seen in figure 2.1.

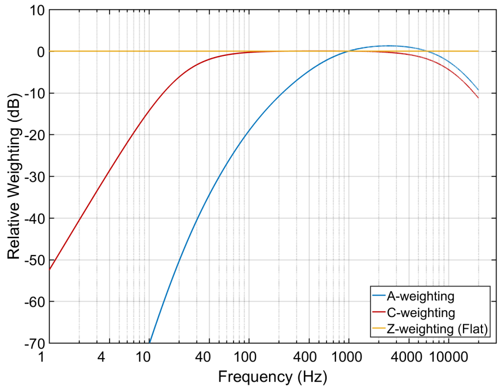


Figure 2.1: Weighting curves calculated from the mathematical functions in the international standard IEC 61672-1:2013. The blue curve represents the A-weighting curve [13].

2.2 Road traffic noise

Road traffic noise is the gathered expression for all noise emission from vehicles existing in the traffic flow. Each and every vehicle will contribute to the noise level emitted from the road traffic and thus the individual noise sources of each vehicle is of importance when understanding what influences the noise emission from road traffic. The most contributing noise sources of a vehicle are the power unit which include the engine, exhaust system and transmission, noise from the interaction between the tyre and road, aerodynamics, brakes and structure-borne noise [14].

The generation of noise from vehicles is composed of a majority of different mechanisms. Propulsion noise, which is referred to as the noise from the power unit and its belongings, dominates the noise in low speeds. As the speed increases the noise from the interaction of the road surface and the tyre becomes more dominating, referred to as tyre/road noise [15].The speed at which the propulsion noise and tyre/road noise is equal is called the cross-over speed.

The different sources of the vehicles contributes to the total noise emitted. Thus the noise generating mechanism of propulsion and tyre/rode are the most dominating noise sources from a car driving in legal speed limits as seen in figure 2.2. The speed of the vehicle needs to reach around 110 km/h for aerodynamic noise to reach the

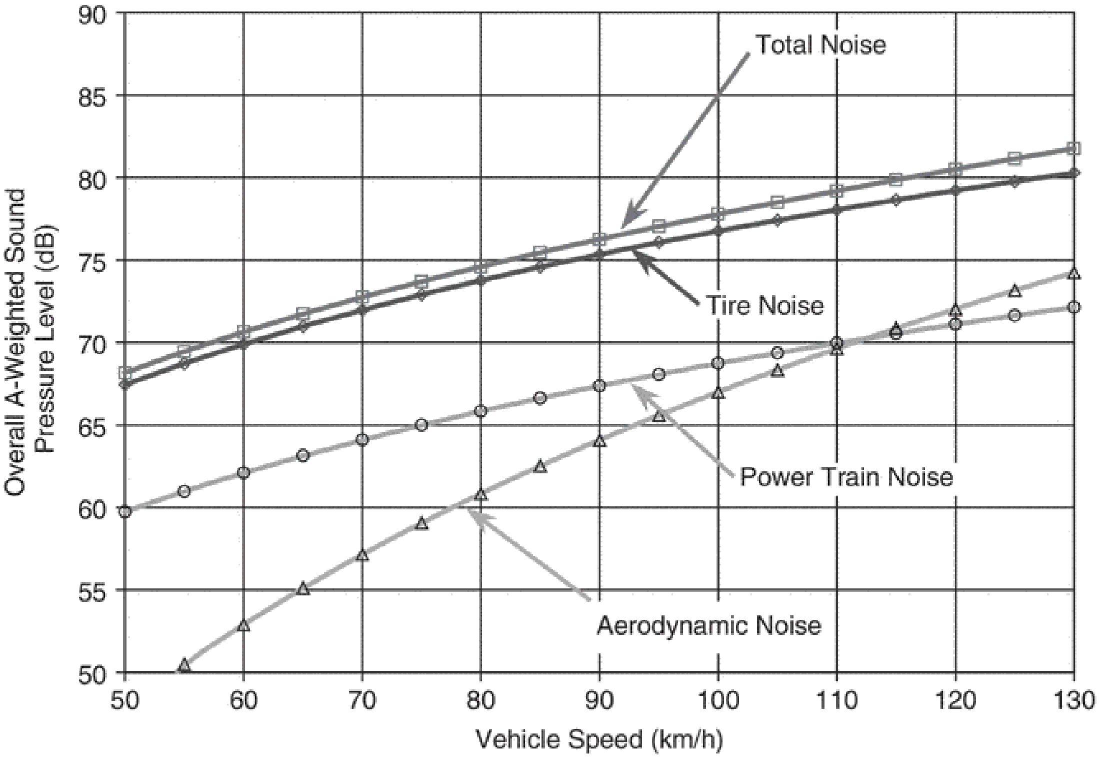


Figure 2.2: The different contribution of noise sources of a passenger car to the total noise as a function of speed [16].

same level as the propulsion noise which still is clearly dominated by the tyre/road noise. Therefor the contribution of aerodynamic noise and its theory is out of the scope for this report. Noteworthy is that aerodynamic noise can dominate the frequency range between 330 Hz and 900 Hz at 70 km/h but this is still over the investigated speed of this report [16]. Meteorological parameters as air temperature, wind and precipitation influences the noise emission from road traffic but is not regarded since it is out of the scope for this report.

2.2.1 Propulsion noise

The propulsion noise includes all the noise from parts of the vehicles that contributes to its propulsion such as the engine, exhaust system, air intake system, gear, transmission and so forth. Propulsion noise can also be referred to as power train noise or power unit noise. For vehicles with internal combustion engines the propulsion noise is more related to the engine speed and load rather then the speed of the vehicle [17]. This is because of the impact of the chosen gear that affects the speed of the engine. Engines running on petrol or diesel have different combustion systems which leads to distinct noise characteristics.

2.2.2 Tyre/road noise

The generation mechanisms of noise from the interaction of the tyre rolling over the road surface is produced by a combination of physical processes. The levels of tyre/road noise is strongly influenced by the speed of the vehicle which affects these mechanisms. These mechanisms have been explored since the 1970's and is commonly accepted within the research world, nevertheless the impact of how strongly each of these mechanisms contribute are disputed [15][17]. The physical process that influences the generation mechanisms of tyre/road noise can be divided into following groups:

- Impact mechanisms
- Adhesion mechanisms
- Aerodynamic mechanisms

The generation of noise from the impact mechanism is fundamentally caused by the variation of interaction forces of the tyre treads as they interfere with the road surface and vibrations develops. The vibrations develops by the impact and deflection of the tread block when it is in contact with the road surface. Vibrations are created as the tread block enters the road surface and spreads mostly radially into the tyre. The tread blocks will upon leaving the interaction with the road surface return to its originally form under rapid movements creating both tangential and radial vibrations spreading into the tyre. These mechanism can be seen in figure 2.3.

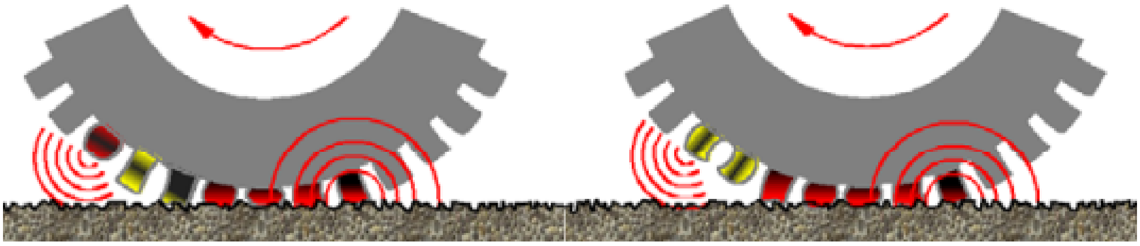
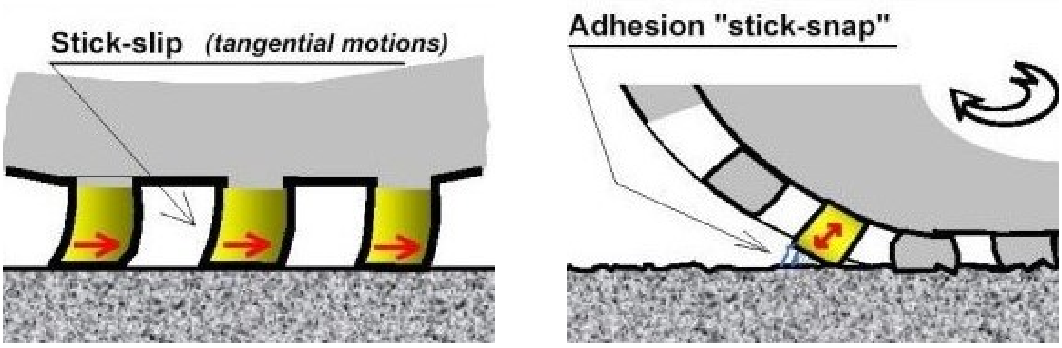


Figure 2.3: Visualisation of how the tangential and radial vibrations are created as a result of the forces acting at the tyre treads [15].

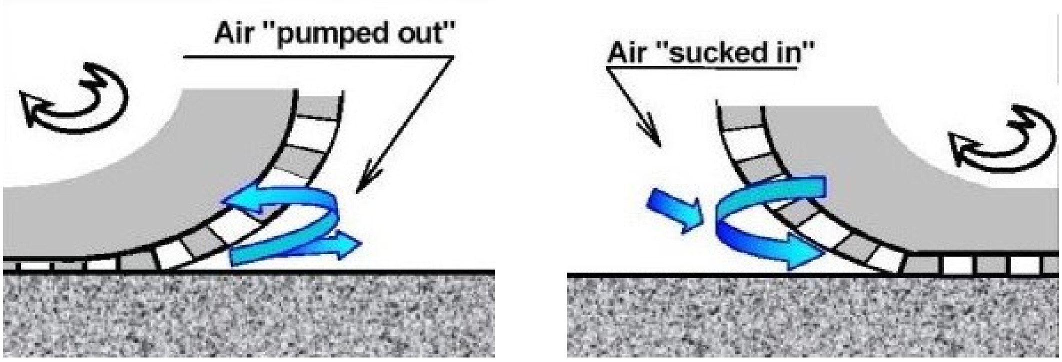
The adhesion mechanisms of noise generation mainly exist within the footprint of the interaction between the tyre and the road surface. As the tyre tread blocks comes in contact with the road surface it is subject to horizontal forces which when exceeds to frictional forces will cause the tyre to "slip" momentarily before it "sticks" to the road surface again. This can be seen in figure 2.4a. This stick/slip mechanism mainly occur when a tyre is subject to great side forces (cornering), accelerating or breaking and is perceived as a squealing noise [17]. In addition another mechanism related to the previous mentioned is the stick-snap mechanism. This occurs when the tyre tread becomes "sticky" and drives over a smooth and clean surface, increasing the adhesive bond between the tyre tread and road surface. The rubber of the tyre tread will be stretched before it is released from the road surface causing vibrations in the tread elements as the rubber returns to its original shape and is perceived as a "snap" seen in figure 2.4b.



(a) (b)

Figure 2.4: Visualised adhesion mechanisms created by the contact between the tyre and road. From reference [17], used with permission.

The aerodynamic mechanisms are caused by the turbulence of air around and between the tyre and its treads rolling over the road surface. It consist partly of turbulence of air being displaced by the tyre driving over the road surface and air being dragged around the spinning rim of the tyre. The effect of this process has not been proved to contribute significantly to the over all levels of aerodynamic tyre/road noise as long as not operating at speed limits well above the normal speed limits of high ways [17]. Another mechanism is the so called "air-pumping" which was originally described by Hayden [18] and is caused by the sudden change of volume within the air cavity of the tyre tread's grooves and road surface texture. When the tyre treads comes in contact with the road surface, the volume of air cavity is being reduced since the treads are being compressed and air flows out. In a time sequence short after when the tyre tread starts to leave the contact surface the inflow of air in the decompressed cavity of the tread restoring the size of the cavity [19]. Thus this mechanism of air being pumped in and out of the tyre results in air pressure fluctuations heard as noise and the mechanism described can be seen in figure 2.5.



(a) **(b)**

Figure 2.5: Visualisation of aerodynamic noise generation mechanism called air pumping. From reference [17], used with permission.

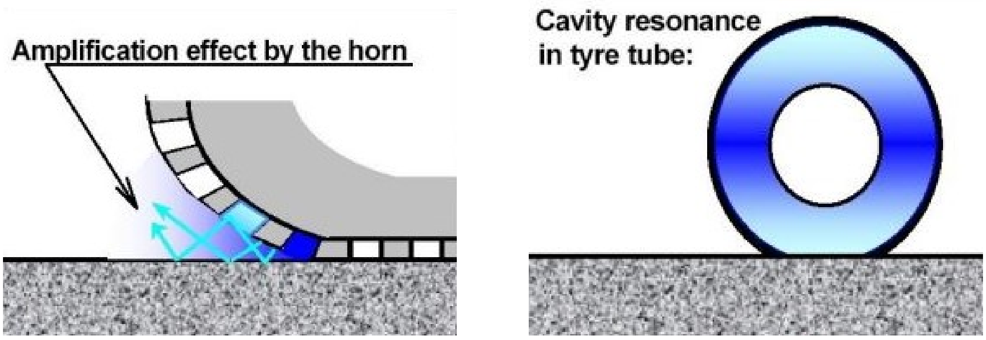
2.2.3 Sound enhancement mechanisms

The sound energy of these noise generation mechanisms between the tyre treads and the road surface alone will not radiate noise efficiently because of the small proportion of the tread blocks resulting in being poor radiators. The mechanism within the tyre/road system that amplifies these generation mechanism are referred to as sound enhancement mechanisms. The main sound enhancement mechanisms are:

- The horn effect
- Helmholtz resonators and organ pipes
- Tyre resonances

The horn effect arises at the front and back of the tyre at the interaction area between the tyre and road surface which creates a narrow throat that acoustically can be seen as a horn seen in figure 2.6. Since much of the noise is generated and radiated in this intersection the acoustically horn enables the amplification of noise to be increased because of the radiation being more efficient [17].

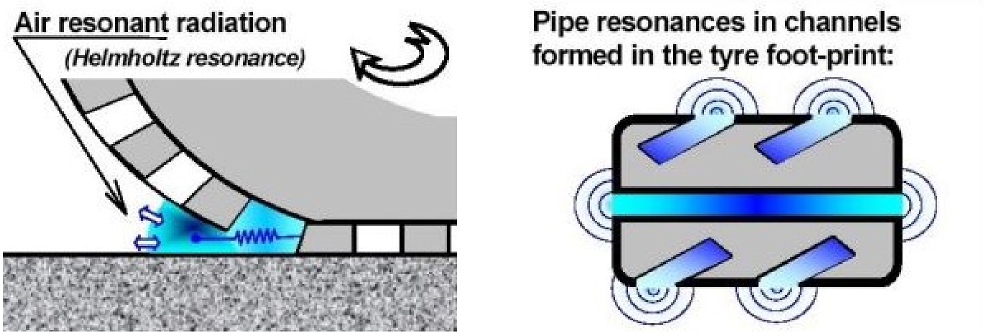
The acoustic cavity within the tyre is excited to vibrations from the tyre producing resonances at certain frequencies. These resonances are depended only of the tyre, the size of the rim and the speed of sound in the medium of the tyre. The contribution of the noise from the resonances are more important for the acoustical environment within the car then for the exterior noise of vehicles, at least for passenger cars [17].



(a) (b)

Figure 2.6: Visualisation of two sound enhancement mechanisms. From reference [17], used with permission.

The tyre treads in the contact patch between the tyre and road surface takes on a form of acoustical systems enhancing the noise radiated. At the interaction in the contact patch at the back of the tyre a Helmholtz resonator occurs representing a simple mass-spring system. The air volume of the cavity leaving the contact with the road surface acts as a spring and the air present between the tread and road surface becomes a mass. The mass spring system occurs at the moment the cavity of the tyre tread opens up to the air behind the tyre resulting in a resonance. Resonances also occurs due to standing waves in the grooves of the tyre between the tyre and road surface often called "pipe resonators". These sound enhancement mechanisms can be seen in figure 2.7



(a) (b)

Figure 2.7: Visualisation of two sound enhancement mechanisms. From reference [17], used with permission.

2.3 CNOSSOS-EU

Common Noise Assessment Methods in Europe also known as CNOSSOS-EU is a strategic noise mapping method developed by the European Commission during 2009-2012. The background of the development of the method originates from The Environmental Noise Directive (2002/49/EC) which states that countries that are a part of EU needs to determine the environmental noise pollution by noise mapping of the road traffic, railway traffic, industrial and aircraft noise. The countries are since June 2007 obliged to produce strategic noise maps over the largest roads, railways and airport every 5 year. This created a need for a common noise assessment method which all the countries could use to produce comparable results [9].

The valid frequency range to implement the CNOSSOS-EU method for road traffic noise is between 125 Hz to 4000 Hz. The method calculates the results in octave band for the given frequency interval.

2.3.1 Vehicle category and noise source

In the CNOSSOS-EU method each an every single vehicle contribute to the total traffic flow which determine the road traffic noise source. The vehicles are categorized into four different categories which are:

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

There is additionally a fifth category which is open to new vehicles which deviates in great extent from the earlier four categories in regards of noise emission. This might for example be electric or hybrid vehicles if it is established that the noise emission differ [9] The properties of each category is defined in appendix A.1 but it is only category 1 which is investigated within the scope of this report.

In the CNOSSOS-EU method the noise source of each vehicle belonging to category 1 is represented of one single point source placed 0.05 m over the ground as in figure 2.8.

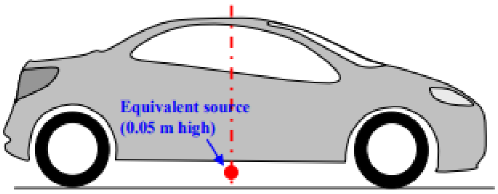


Figure 2.8: Visualisation of how the noise source is defined in the CNOSSOS-EU method [9].

2.3.2 Sound power emission of single vehicles

The sound power emission from each vehicle in the calculation method is defined by which category it belongs to and its speed. It is also corrected with regard to environmental effects. The total sound power emitted from a single vehicle is dependent of the two main noise sources from road vehicles which are the rolling noise as an effect of the tyre/road noise and propulsion noise. For vehicles in category 1 the total sound power equals the energetic summation of propulsion and rolling noise together and is defined by:

$$L_{W,i,m} = 10 \cdot \log(10^{\frac{L_{WR,i,m}(v_m)}{10}} + 10^{\frac{L_{WP,i,m}(v_m)}{10}}) \tag{2.6}$$

where $L_{WR,i,m}$ is the sound power originated from the rolling noise and $L_{WP,i,m}$ is from the propulsion noise [9]. Calculations for each term is given and explained below.

2.3.3 Rolling noise and correction factors

The sound power originating from the rolling noise is given in CNOSSOS by:

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m} \cdot \log(\frac{v_m}{v_{ref}}) + \Delta L_{WR,i,m}(v_m) \tag{2.7}$$

where $A_{R,i,m}$ and $B_{R,i,m}$ are given in appendix A.2 for vehicles in category 1 with a reference speed of 70 km/h. The correction factor, $\Delta L_{WR,i,m}$, is a sum of each correction factor that is applied for the rolling noise emission by:

$$\Delta L_{WR,i,m}(v_m) = \Delta L_{WR,road,i,m}(v_m)+\Delta L_{studdedtyres,i,m=1}(v_m)+\Delta L_{WR,acc,i,m}(v_m)+\Delta L_{W,temp}(\pi) \tag{2.8}$$

where $\Delta L_{WR,road,i,m}$ governs the effect of the rolling noise at a different road surfaces difference from the properties of the reference surface. $\Delta L_{studdedtyres,i,m=1}$ is applied as a correction factor for the number of light vehicles with studded tyres. $\Delta L_{WR,acc,i,m}(v_m)$ accounts for the differences in rolling noise as an effect of variations of speed in urban driving environment. $\Delta L_{W,temp}(\pi)$ is a correction factor with the average temperature π difference from the reference temperature $\pi_{ref} = 20$ [9].

2.3.4 Propulsion noise and correction factors

The emission of the propulsion noise accumulates the noise from the engine, exhaust, air intake, gears etc. The sound power emission from the propulsion noise is given by:

$$L_{WP,i,m} = A_{P,i,m} + B_{P,i,m} \cdot (\frac{v_m - v_{ref}}{v_{ref}}) + \Delta L_{WP,i,m}(v_m) \tag{2.9}$$

where $A_{P,i,m}$ and $B_{P,i,m}$ is given in appendix A.2 for vehicles in category 1. $L_{WP,i,m}$ is the sum of the correction factor that should be applied to the propulsion noise for differentiating driving conditions or specific regional conditions. It is given by:

$$\Delta L_{WP,i,m}(v_m) = \Delta L_{WP,road,i,m}(v_m) + \Delta L_{WP,acc,i,m}(v_m) + \Delta L_{WP,grad,i,m}(v_m) \tag{2.10}$$

where $\Delta L_{WP,road,i,m}(v_m)$ regards the influence of the road surface at the propulsion noise. $\Delta L_{WP,acc,i,m}$ and $\Delta L_{WP,grad,i,m}$ covers the influence of the driving conditions different from the reference situation effecting the propulsion noise [9].

2.4 Psychoacoustics

Physical measurement values can be insufficient to determine whether a sound will cause nuisance for the listener, thus psychoacoustics can help create a broader picture and understanding of the perceived noise disturbance. Psychoacoustics is an interdisciplinary field involving acoustics, physics, physiology, psychology and biology to mention a few. When humans hear a sound it is not only the pure mechanical phenomenon of the sound that is influencing how we hear it but also the perception. Psychoacoustics explores the physical mechanism of sound and its relation with the interception in the human auditory system. Different models have been developed for these relations and since psychoacoustics is an interdisciplinary field these methods can differ depending of the approach and concept developed [20].

Zwicker developed the model for psychoacoustic annoyance (PA) which aims to describe the annoying characteristics of a sound by a combination of hearing sensations as loudness, sharpness, roughness and fluctuation strength [21]. These psychoacoustic parameters will be defined in coming subsections.

2.4.1 Critical-band rate

The critical-band rate was established by Spencer in 1933 and later refined in 1940. The critical-band rate originates from the knowledge of the cochlea in the human ear and its ability to distinguish separate frequencies. The human ear can normally hear sound between 20 Hz and 20 000 Hz but the possibility to separate two tones decreases as a function of the increasing frequency. The critical-band rate can be compared to bandpass filters as they have a centre frequency, f_c, and a bandwidth. Each bandwidth is referred to as a "Bark" and there is a total of twenty-four critical bands [21].

2.4.2 Loudness and loudness level

Loudness is a subjective parameter in psychoacoustics which aims to explain how loud or soft a sound is perceived by humans. For a more precise definition of loudness Moore states: "Loudness is defined as that attribute of auditory sensation in terms of which sounds can be ordered on a scale extending from quiet to loud" [22]. Loudness is the human sensation which corresponds most closely to the sound intensity of the sound. The unit expressing loudness is sone and the reference value which equals 1 sone is normally a 1 kHz tone at a level of 40 dB. A doubling or halving of the loudness perceived by humans are represented by an increment/decrement of about 10 dB for the 1 kHz tone. This holds for levels above 40 dB as for lower levels smaller differences are needed to obtain a doubling or halving of the loudness [21].

Loudness levels enables to achieve more precise results than just magnitude estimations and because of this the loudness level was introduced by Barkenhausen in the early 1920s. The purpose of the loudness level was to characterize the loudness of any sound. The loudness level, contrary to the sensation value loudness, is a value between sensation and physical values. Loudness level is expressed in its unit phon and it is equal to the SPL for a sound of a 1 kHz tone in a plane wave and frontal incidence. The most common used loudness level is defined for pure tones of different frequencies and are called equal loudness curves [21]. Loudness, denoted N, is calculated from the integral of specific loudness, denoted N', over all critical-band rates:

$$N = \int_0^{24Bark} N' dz. \tag{2.11}$$

2.4.3 Sharpness

Sharpness, denoted S, is another psychoacoustic parameter which is a sensation value. The unit for sharpness is acum and one acum is defined by a narrow-band noise, which is one band width wide at the centre frequency of 1 kHz and has a level of 60 dB. It is possible to compare the sharpness between two different noises, thus the sharpness can be judged likewise loudness as being doubled or halved. In contrary to loudness, sharpness is not dependent of the level increment to the same extent as loudness since an increment from 30 dB to 90 dB corresponds to an increment of the sharpness by a factor of 2. This leads to that if the sharpness of two sounds are to be compared and the level difference is not obvious it can be ignored as a first approximation. The most important parameters influencing the sharpness is the spectral envelope and the centre frequency of narrow-band noise. A sound with a spectral envelope containing more high frequencies is perceived as being sharper [21].

The boundary condition of a narrow-band noise with a center frequency of 1 KHz resulting in the sharpness of 1 acum is given by following equation:

$$S = 0.11 \frac{\int_0^{24Bark} N' g(z) z \, dz}{\int_0^{24Bark} N' \, dz} \text{ (acum)} \tag{2.12}$$

here S is the sharpness, the total loudness is calculated in the denominator and where the expression in the nominator is the specific loudness over the critical-band rate with an addition of the factor g(z) which depends on the critical-band rate. The factor g(z) increases from 1 for critical-band rates over 16 Bark up to 4 at 24 Bark [21].

2.4.4 Fluctuation strength

Sounds which are modulated evokes three different hearing sensations whereas two of them are referred to as psychoacoustic parameters. Fluctuation strength, denoted F, is a hearing sensation produced at lower modulation frequencies up to around 20 Hz. The sensation of loudness shifting up and down slowly is perceived as fluctuation and reaches a maximum around 4 Hz. The fluctuation strength has the unit vacil and its reference is given of a 60 dB 1 kHz tone with 100 % amplitude-modulation at 4 Hz, accumulating one vacil [21].

2.4.5 Roughness

As mentioned above modulated sounds evoke three different hearing sensations where the first one is for low modulation frequencies up to 20 Hz and is perceived as being fluctuating. When the modulation frequency increases a new hearing sensation is perceived called roughness, denoted R, which normally starts at around 15 Hz and reaches its maximum around a modulation frequency of 70 Hz. As the modulation frequency increases after 70 Hz the roughness decreases and reaching larger modulation frequencies enables us to detect three separate tones within the noise. The definition of 1 asper is a 100% amplitude modulated tone of 1 kHz at a modulation frequency at 70 Hz in 60 dB. The roughness of sounds can be obtained in the frequency range approximately between 15 Hz to 300 Hz [21].

2.4.6 Psychoacoustic annoyance

PA aims to quantitatively describe the annoyance perceived in a psychoacoustical evaluation of a sound. It depends on the parameters loudness, sharpness, fluctuation strength and roughness and is given by equation 2.13.

$$PA = N_5(1 + \sqrt{w_S^2 + w_{FR}^2}) \tag{2.13}$$

here N_5 is the five percentile of loudness in sone,

$$w_S = (\frac{S}{acum} - 1.75) \cdot 0.25 \ \log_{10}(\frac{N_5}{sone} + 10) \text{ for } S > 1.7 \text{ acum} \tag{2.14}$$

which describes the influence of the sharpness and

$$w_{FR} = \frac{2.18}{(\frac{N_5}{sone})^{0.4}} \cdot (0.4 \cdot \frac{F}{vacil} + 0.6 \cdot \frac{R}{asper}) \tag{2.15}$$

which describes the impact of the fluctuation strength and roughness [21].

3

Literature review

This literature review is a part of the report to gather and present state of the art research and knowledge within the scope of the report. The purpose besides gathering and presenting the research is to shed light at gaps within the research whereas the work of this report fills a purpose to contribute to increased knowledge. The need of research about noise emission from EVs are important since EVs and especially electric passenger cars becomes increasingly more frequent at the roads and are expected to increase in the future. It is often assumed by the general population that EVs are quieter than ICEVs, thus a noise reduction of the road traffic noise can be achieved when the vehicle fleet will be converted to mainly EVs in the future. Whether this assumption is true or not will be investigated within this literature review and if so to what extend EV are more quieter.

As seen in the section above the noise emission from vehicles mainly consists of propulsion noise and tyre/road noise. The dominating source depends strongly of the speed of the car. The potential noise reduction gain from a shifting vehicle fleet distribution is expected to reduce as the tyre/road noise starts to dominate since it is mainly the propulsion noise that deviates between the different vehicle types. This indicates that the noise reduction for the most part will concern lower speeds. It is still of interest since the travelling speed in cities can be within this range and consequently influenced. In addition the frequency content of the noise is of interest since it influences the perception of the noise. The frequency content affect the SPL weighting and also psychoacoustic parameters which could result in deviations of the perceived noise.

The noise emission from EVs compared with ICEVs were chosen to delimit the literature review. Since the noise emission is affected by many aspects, certain questions were chosen to further delimit the literature review and can be seen below:

1. Is there a difference between the measured noise emission from EVs and ICEVs at constant speeds?
2. How does the speed influence the possible deviation of noise emission between the two vehicle types?
3. How does the frequency spectrum of noise at constant speed from EVs compare to ICEVs?
4. Measured values can sometimes be insufficient to describe the perceived annoyance of the noise. How are noise from EVs perceived relative to ICEVs?

3.1 Measurements of EVs and ICEVs

A French study presented in 2001 compared an ICEV, HEV and an EV in order to predict how the noise emission from vehicles could be affected in the upcoming change of vehicle fleet distribution. The A-weighted maximum value L_{Amax} was measured 7.5 m from the drive line of the vehicle and 1.2 m above the ground. Information of type of tyre and engine is presented but complement information as curb weight etc. is missing [23]. The EV and HEV are more quieter than the ICEV seen in figure 3.1 where it is distinctly for the lower speed limits up to 50 km/h. The noise emission after passing 50 km/h from the different vehicle types are relative close. Furthermore the impact of the selected gear for the noise emission of the ICEV is captured in the figure. The larger differences seen when the ICEV is driven at gear 1 and 2 are strongly correlated to the propulsion noise of the ICEV. The differences are as large as more than 10 dBA at the lowest speed and is still greater than 5 dBA at 30 km/h. It is not until 50 km/h and shifting to gear 3 as the noise level converges and reaches almost equivalent levels.

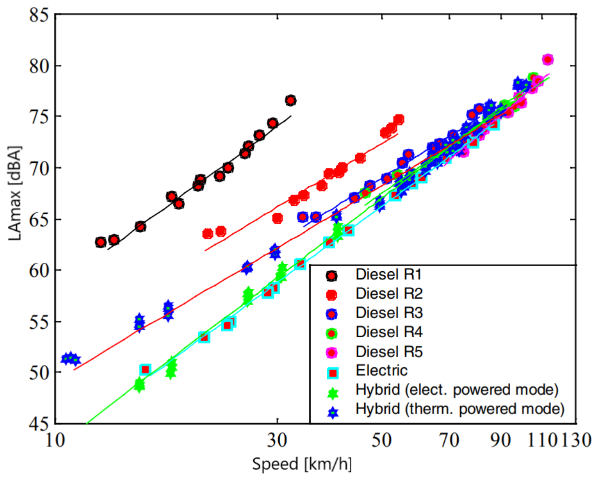


Figure 3.1: Comparison of the maximum A-weighted SPL between a diesel car in gear 1-5, HEV and EV. The speed of the vehicles are constant [23].

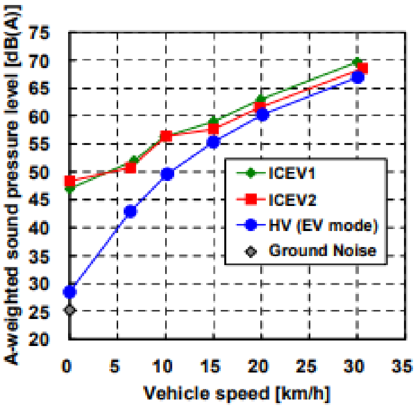


Figure 3.2: Comparisons of the measurements between two ICEV and one HV operating in electrical mode [24]

EVs have also raised concerns for pedestrians safety in the traffic regarding being to silent in slower speeds thus being heard or seen to late. The ability for pedestrians and especially for visually-impaired pedestrians to hear an approaching vehicle is crucial for the detection of it. Therefor a study took place in Japan in 2010 where measurements of two ICEV and one HEV operating in electrical mode was performed. In addition the possibility to implement a sound emitted from vehicles driving in slow speeds was discussed called Approaching Vehicle Audible System (AVAS) [24]. The maximum SPL emitted from the vehicles was measured at speed up to 30 km/h and are presented in figure 3.2. The study did not present what type of cars that were used neither how the car was driven. Later in the study small passenger cars were used when doing a jury test where people judged how they heard the approaching vehicle so it is not far-fetched to assume that the measurements were done with the same small passenger cars. The speed in which the vehicles are operating are assumed to be constant. From the study it can be seen that the HEV operating in electrical mode emits less noise up to approximately 20 km/h before the noise levels are almost equivalent.

CityHush was a project within the European Union working with reducing the road traffic noise in urban environments. A part of the project was about how introducing quiet-zones (Q-Zones), where only certain vehicles are granted free access based on the noise emitted, could reduce the noise levels. The aim of the project was to determine suitable noise criteria for the vehicles which should be able to access freely and was only regarding passenger cars. During the project measurements of EVs and HEVs were carried out with the ECE R51 method B which is a method based on the ISO 362-1:2007 measurement standard. Earlier collected data from measurements of cooperating partners to the project were also used. The noise was measured at 7.5 m from the drive line and 1.2 m above the ground [25]. The results from the earlier collected data and measurements can be seen in figure 3.3. The value of interest within the scope of this report is the constant speed test, denoted L_{crs}, which is performed at a constant speed of 50 km/h. It is reasonable to compare pure electric car with the small car since all measured EVs had low kerb weights. The difference is still approximately 7 to 8 dBA between them at constant speed of 50 km/h in an urban environment.

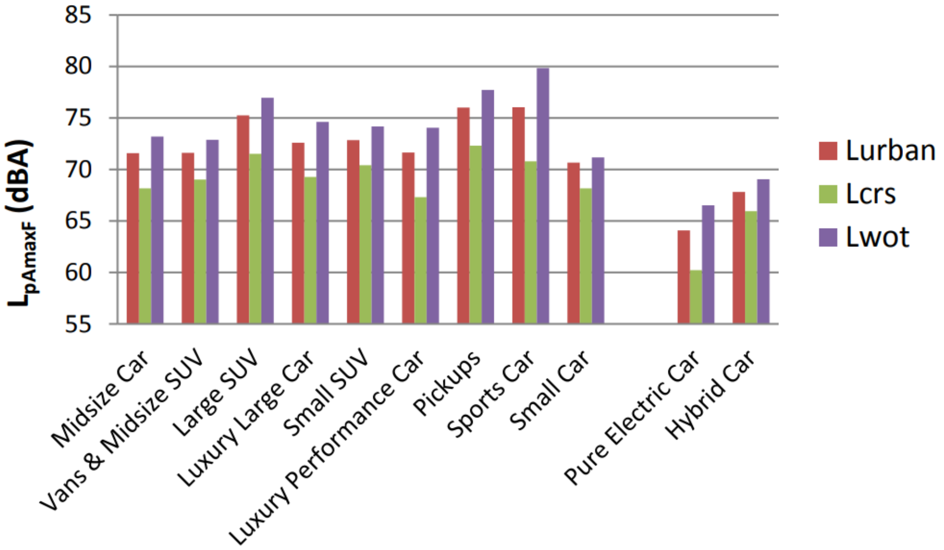


Figure 3.3: Measured and collected data of noise emission from passenger cars in CithyHush project [25]

Table 3.1: Measured maximum SPL from five vehicles in the study from Japan [26].

Vehicle type	10 km/h	20km/h
ICE-1	56.7	61.7
ICE-2	57.9	61.9
EV-1	50.2	61.0
EV-2	47.9	57.2
HV-1	49.9	60.1

In the following up study of pedestrian safety in Japan during 2012 new measurements was performed with two EVs, one HEV and two ICEVs operating at 10 km/h and 20 km/h. The purpose was again to evaluate how the implemented AVAS-system was perceived and whether electrical vehicles were too quiet for pedestrians to hear. The measurement were made at a distance of 2 m from the center of the drive line of the vehicles and the microphone was placed 1.2 m above the ground [26]. The specifications of the vehicles can be seen in [26]. The dimension of EV-1 and ICE-2 are more similar and EV-2 and ICE-1 are more similar. The results of the measurement are presented in table 3.1. At 10 km/h the EVs are around 7 to 10 dB quieter and this is limited to being only around 0.9 to 4.5 dB at 20 km/h.

Van Blokland describes in *Stimulation of low noise road vehicles in the Netherlands* how the Netherlands stimulate and enforce the use of more silent vehicles within the country. The expected noise reduction is more significant for trucks and related heavy vehicles than for passenger cars since the cross over speed is around 30 km/h for passenger cars [27]. Measurements of a car with electric motor and a ICEV is compared at 7.5 m from the drive line and seen in figure 3.4. The appearances and dimension of the cars are not presented limiting the possibility to compare with other studies. As seen in the figure the greatest deviations occurs at lower speeds. From 20 km/h up to 40 km/h the deviations are about 2 to 4 dBA and after passing 40 km/h it becomes insignificantly small.

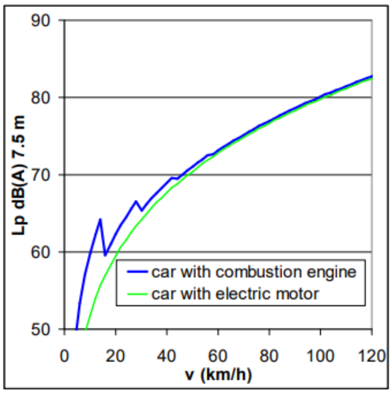


Figure 3.4: Comparison of noise emission from EVs and vehicles with ICEVs [27].

In an American study from 2012 measurements of plug-in HEV operating in complete electric mode were presented. The vehicle used was a mid sized passenger car Chevrolet Volt and the vehicle speeds measured were from 5 mph up to 70 mph with increments of 5 mph at both constant speed and during acceleration. The measurements was performed at two different test tracks and distances of 25 feet and 50 feet. From the measurements the reference energy mean emission level (REMEL) was calculated which is a standardized value used in America to describe the noise emission from a vehicle fleet at any given road. The calculated REMEL value of the EV was then compared to the equivalent for "automobiles" given by the Federal Highway Administration which can be interpreted to represent ICEVs [28]. It can be seen in figure 3.5 that from around 15 mph (around 25km/h) the measured SPLs of the EVs are equal to the value for automobiles and thus the reduction of noise emission is only reduced for speeds up to 15mph from these measurements.

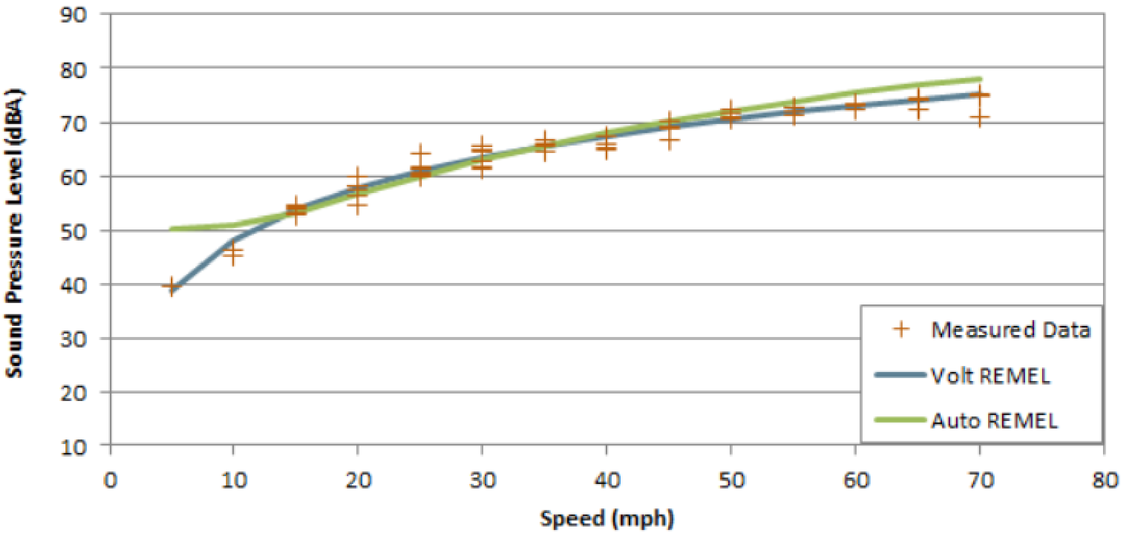


Figure 3.5: Comparison of REMEL curve between the REMEL curve for "automobiles" by FHWA and the measured and calculated REMEL curve of the Chevrolet Volt [28].

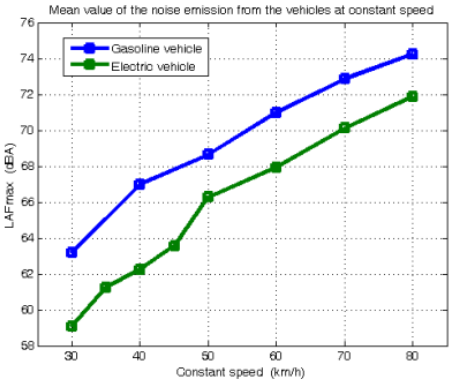


Figure 3.6: Mean value of measurements of the L_{Amax} for an EV and a ICEV at different speeds during CPB measurements [29].

In 2012 the Technical University of Denmark published a master thesis investigating the noise emission between an ICEV with a petrol engine and an EV. A controlled pass-by (CPB) method was used where the microphone was placed 7.5 m from the drive line and 1.2 m above the ground. The EV used was a passenger car Citroën C1 and the corresponding ICEV was a Toyota Aygo with similar appearances and dimension. The same type of tyres were used at both vehicles [29]. The mean value of at least 5 trials at each speed limit of the A-weighted maximum SPL is presented in figure 3.6. It can be seen that the EV emits lower noise levels for all speeds which is noteworthy since the tyre/road noise is expected to dominate at higher speeds resulting in relative equal noise levels. The EV is 2 to 5 dB more quiet in the range between 30 km/h up to 50 km/h.

Dudenhoffer and Hause evaluated in their study *Sound perception of electrical vehicles* the risk of safety concerning the acoustical perception of EVs in urban environment and whether EVs can impose a threat being too quiet for pedestrians to notice in comparison to ICEVs. The comparison of 7 passenger cars driving at a constant speed of 30 km/h were compared. The measurements for a battery electric vehicle (BEV) ranged between 57 to 58 dBA and the corresponding ICEVs measured levels of 59 to 62.5 dBA [30]. The comparison between EVs and ICEVs with similar attributes driving in speed ranges of 10 km/h up to 60 km/h results in lower levels of approximately 1 to 5 dBA where the deviation decreases with increasing speed. Within the same study an EV was measured to emit lower levels of noise up until 30 km/h compared to the ICEV of the same model. Since the EV for the latter comparison had tyres marked with nosier tyres it could be an explanation for why the EV had higher noise levels for the speed range between 30 km/h and 60 km/h of 1 to 2 dBA [5].

As a part of the COMPETT project measurement of two BEVs and two ICEVs were made. A CPB method was used where two vehicles drove at constant speed between 10 km/h up to 60 km/h with increments of 10 km/h to see how electric powered vehicles could affect the road traffic noise in urban environments. The microphones were placed 7.5 m from the center of the driveline and 1.2 m above the ground following the ISO standard SO 11819-1:1997. Measurements of acceleration and deaccelaration were also investigated but are neglected here since it is out of the scope for this report. The vehicles used were an ICEV and electric version of Citroën Berlingo, Nissan Leaf (EV), and Volkswagen Golf (ICEV). The vehicles all had different tyres [5]. The results from the different version of the Citroën Berlingo are seen in figure 3.7 where the electric version is quieter from 10 km/h up to around 30 km/h. It is noteworthy that the electrical vehicle emits louder noise level between 30 km/h and 60 km/h but it is relative small increment which could be explained by the tyres that were mounted at the EV which were expected to be more noisier.

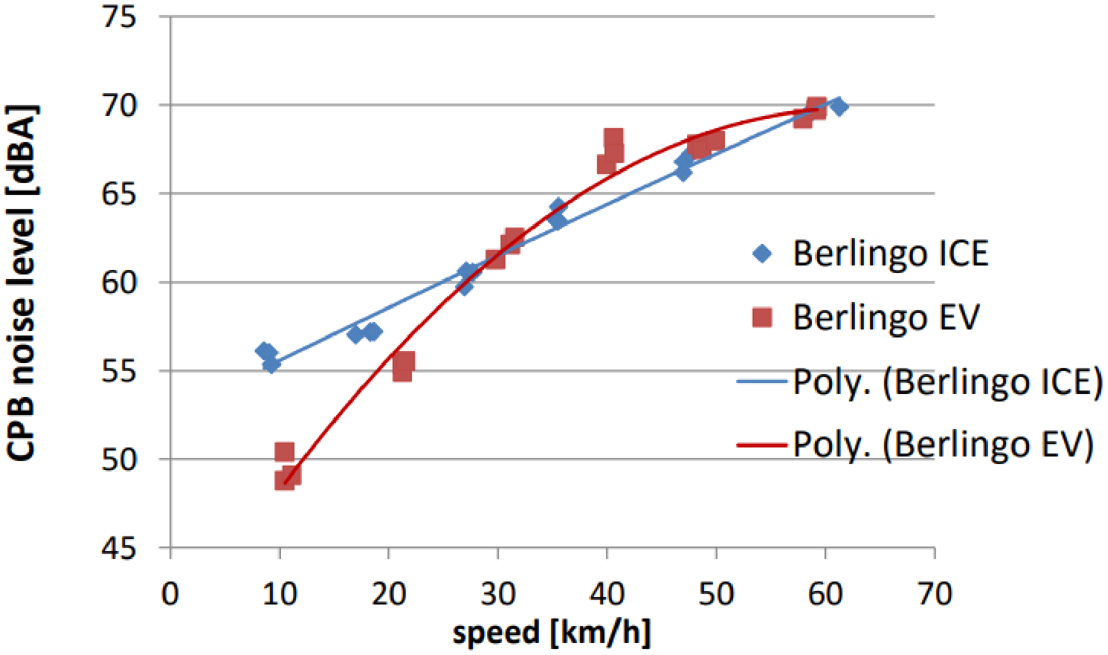


Figure 3.7: Measured noise level of the BEV and ICEV of the Citroën Berlingo from the CPB method and its corresponding polynomial trend lines [5].

The difference between the EV Nissan Leaf and the ICEV Volkswagen Golf are seen in figure 3.8 where the deviation is 4 dB at 10 km/h decreases to only 1.5 dB at 40 km/h and stays around that independent of the increasing speed.

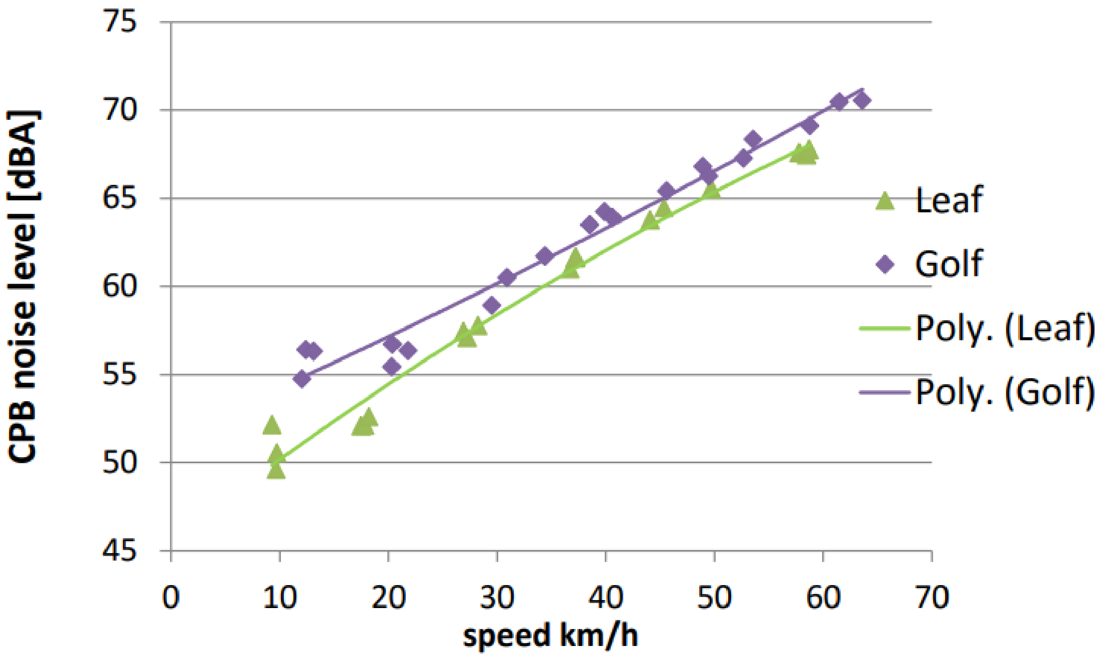


Figure 3.8: Measured noise level of the Nissan Golf (EV) and Volkswagen Golf (ICEV) from the CPB method and its corresponding polynomial trend lines [5].

3.2 Spectra of road traffic noise

To further dive into the possible deviation between the two different vehicle types the spectra of the noise emission from both are of interest. In the same study from 2012 in America the spectra of the EV was compared to the standard FHWA REMEL for automobiles. Two comparisons were made at constant speed of 5 mph representing around 8 km/h and 30 mph corresponding to 48 km/h [28].

As seen in figure 3.9 and figure 3.10 the over all noise levels are lower for the EV. The difference is greater as expected for the lower speed at 5 mph. There is also less low frequency noise emitted from the electric motor compared to the combustion engine. In figure 3.9 at 5 mph the trend of less low frequency is not as explicit since the overall levels are lower but at 30 mph it can be seen that there is a trend from 500 Hz and below of lower noise levels.

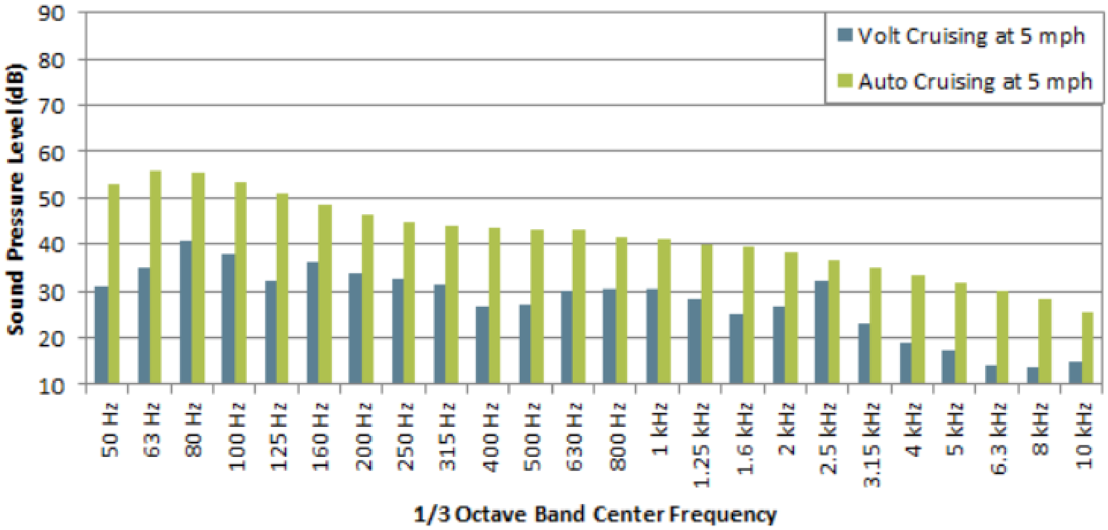


Figure 3.9: Comparison of spectrum at constant speed of 5 mph [28].

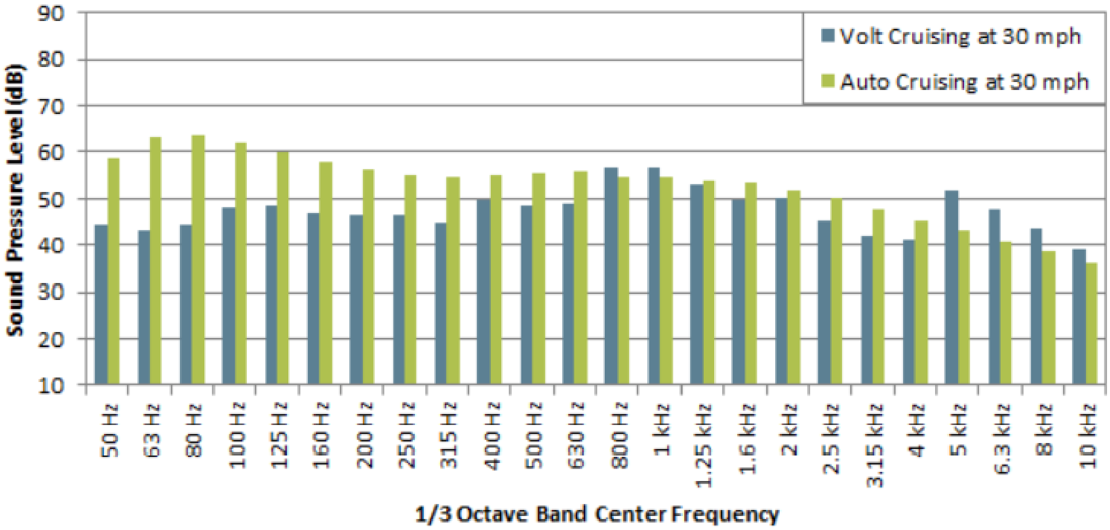


Figure 3.10: Comparison of spectrum at constant speed of 30 mph [28]

The frequency content of the noise from the two EVS and the two ICEVs in the study in Japan 2012 were also analyzed. The vehicles were driven at a constant speed of 10 km/h and 20 km/h. The study do not clarify which gear the ICEVs were using which impacts the result [26]. There are obvious differences seen in figure 3.11 between the ICEVs and EVs above 250 Hz where the relative large deviation can be derived to the propulsion noise of the ICE vehicle.

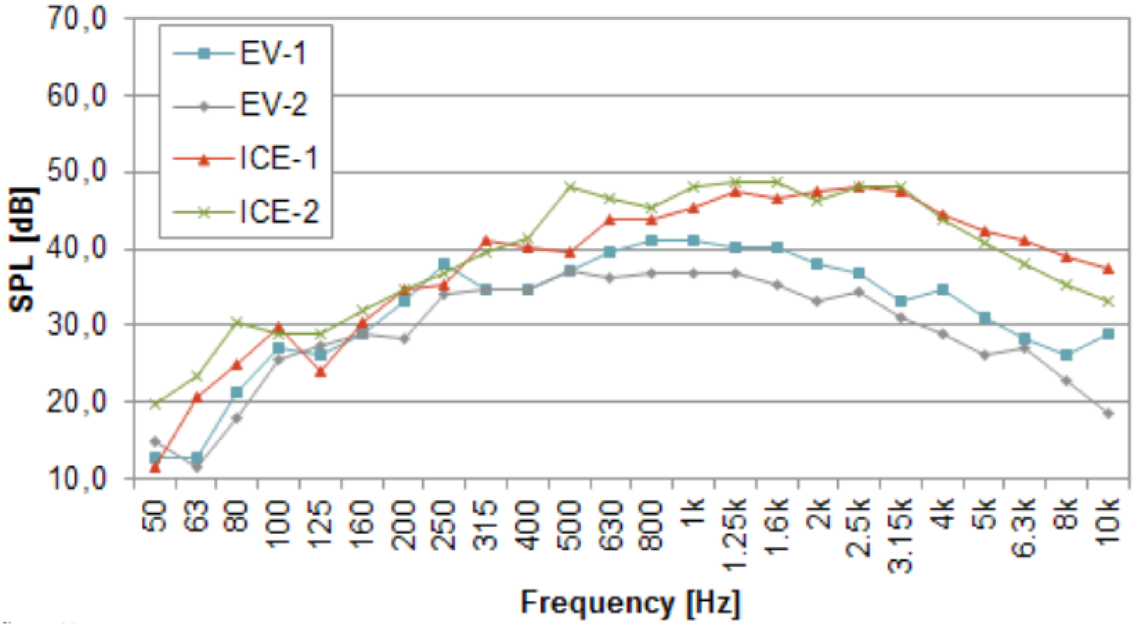


Figure 3.11: Spectrum comparison of measurements of maximum SPL from two EVs and two ICEVs in a study from Japan at a constant speed of 10 km/h[26].

As the speed increases to just 20 km/h the deviations between the different vehicles frequency content decreases. EV-1 generates almost the same noise levels as the ICEVs for the different frequency component up to 2 kHz. EV-2 can be seen to emit lower noise levels at all frequencies travelling at 20 km/h seen in figure 3.12

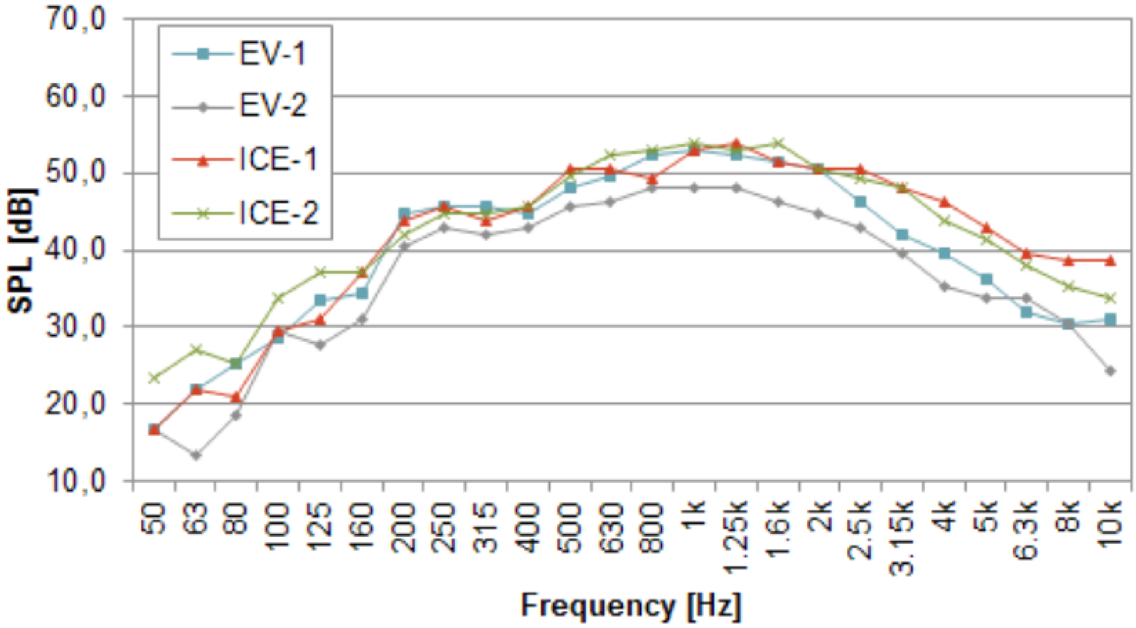


Figure 3.12: Spectrum comparison of measurements of maximum SPL from two EVs and two ICEVs in a study from Japan at a constant speed of 20 km/h [26].

In the previous mentioned COMPETT project analyses of the frequency content was also investigated. The frequency content was analysed at the slowest speed compared with the highest and the vehicles drove at constant speed [5]. Both of the EVs that can be seen in figure 3.13 and 3.14 have narrow peaks at higher frequency and the electric Citroën Berlingo has a peak around 1000 Hz as seen in figure 3.13. The equivalent ICEV Citroën Berlingo also have a first peak in the lower frequencies for both of the speeds but the peak has a lower noise level than the frequency band between 400 Hz to 3150 Hz and thus it is not contributing in a great extent to the total noise level.

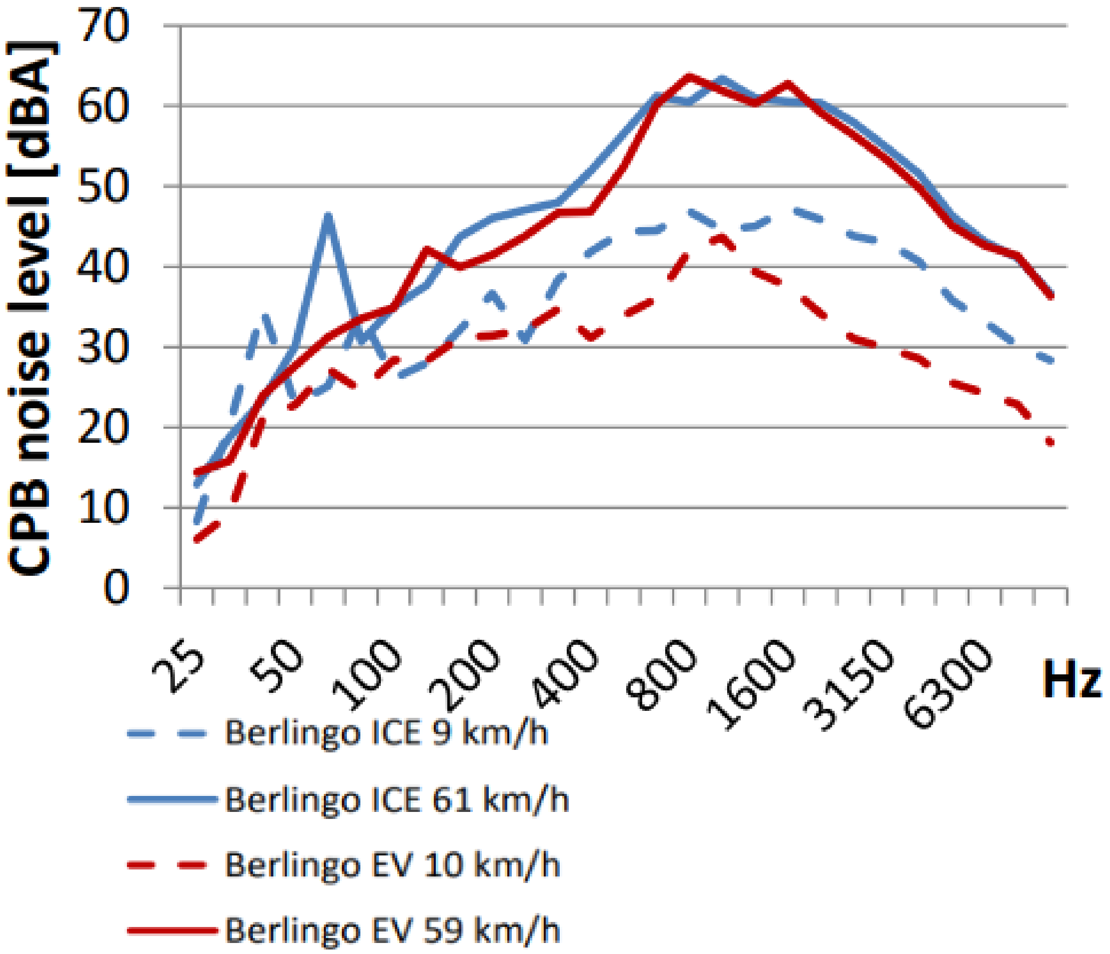


Figure 3.13: Spectrum comparison of the two versions of the Citröen Berlingo at constant speed[5].

In figure 3.14 the results from the EV Nissan Leaf and ICEV Volkswagen Golf are seen. The peak of the Nissan Leaf at low speed is around 2000 Hz in comparison of the frequency content of the EV Nissan Leaf and the ICEV Volkswagen Golf at higher speeds where the peak is around 1000 Hz. The Volkswagen Golf has its first peak in the lower frequency but the peak is lower than the noise level of the overall broad frequency band between 400 Hz to 3150 Hz as for the ICEV Berlingo. The second peak at higher speed are still around 1000 Hz. As seen in in figure 3.13 and 3.14 the frequency content at the higher speed around 60 km/h for both vehicles are around the same expect the peaks for the ICEVs in the lower frequencies.

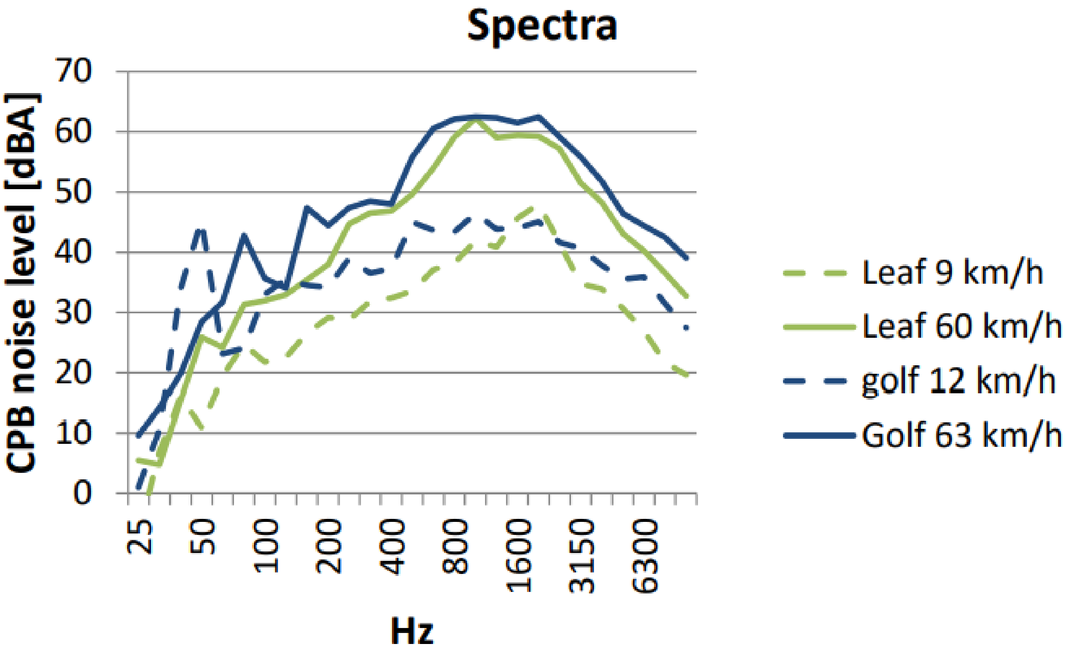
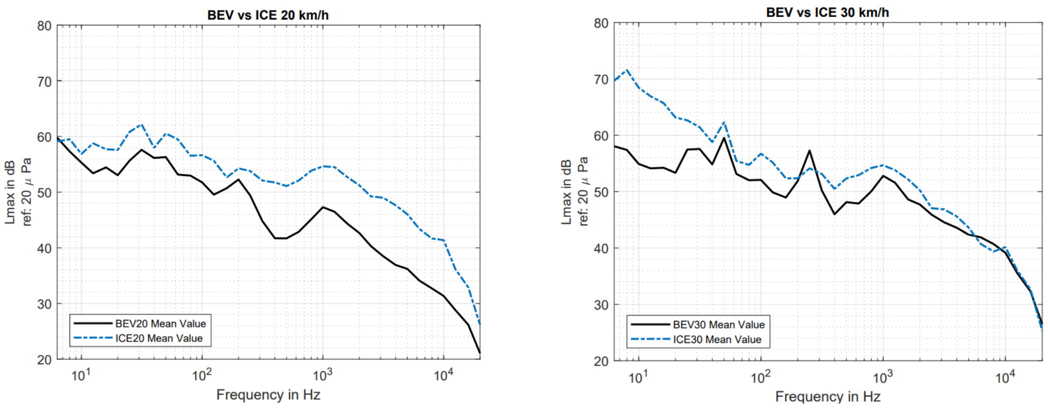


Figure 3.14: Spectrum comparison of the Nissan Leaf and Volksswagen Golf at constant speed [5].

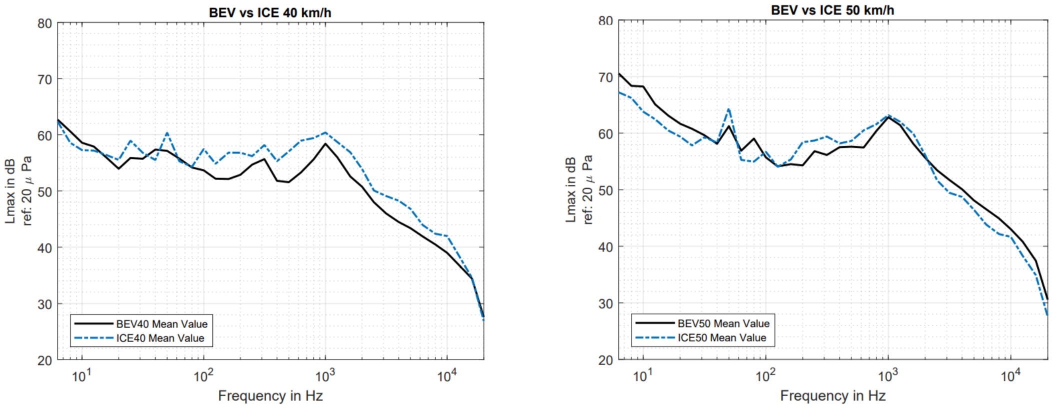
In the master thesis *Potential Noise Reduction with Electric Vehicles* from Chalmers University of Technology published in 2020 which concerned how EVs could affect the possible noise reduction in urban areas in the future, CPB measurements of a BEV and ICEV were used at speeds between 20 km/h and 50 km/h with 10 km/h increments. The frequency content at the speed of 20 km/h and 30 km/h is presented in figure 3.15. The maximum SPL are seen to be lower than the levels from the ICE vehicle for almost all frequencies but the BEV seems to have peek values around 200 Hz to 300 Hz and again at 1000 Hz. The peak at 50 Hz present in figure 3.15b is influenced by the background noise.



(a) Constant speed of 20 km/h **(b)** Constant speed of 30 km/h

Figure 3.15: Spectrum comparison of L_{max} [7].

The noise levels emitted by the vehicles become more and more equal as the speed increases. The frequency content also becomes more similar. This is probably explained by the fact that the tyre/road noise is dominating at higher speed and thus the deviation in the engine noise is not audible. This can be seen in figure 3.16



(a) Constant speed of 40 km/h **(b)** Constant speed of 50 km/h

Figure 3.16: Spectrum comparison of L_{max} [7].

3.3 Psychoacoustics

Even though most of the found research within this literature review has focused at objective measurements some research were found with regards to psychoacoustics and how noise from road traffic but also railway traffic is perceived.

In the earlier mentioned experimental study of Dudenhoffer and Hause 240 participants were also asked to rate how they perceived the noise of both BEVs and ICEVs in an urban environment where passenger cars drove at a speed of 30 km/h. The passenger cars passed the participants which then crossed the street and answered a semantic survey of how they perceived the noise. The study concluded that there are only small differences between the perception of noise from BEVs and ICEVs at a speed of 30 km/h [30].

In a master thesis presented from Norwegian University of Science and Technology in 2019 the noise from railways in Oslo were investigated. Objective measurements were made at four different locations in Oslo and the psychoacoustic parameters of loudness, sharpness, roughness, fluctuation strength, tonality and impulsiveness were calculated. A listening test was then conducted where people were asked to rate how annoying they thought the 53 different recordings were at an 11 graded scale from 0 to 10. The psychoacoustic parameters and the SPL measured were then compared to the annoyance to find the correlation. It was found that for non-sharp noises the A-weighted SPL or loudness correlated well with the annoyance rated in the listening test. Noise with more high frequency content which did not receive high values in neither SPL or loudness were still rated high in annoyance and correlated better with the sharpness which then had high values. It was established by linear regression analyses that the sharpness together with either A-weighted SPL or loudness yielded the results closest to the annoyance rated in the listening test [8].

3.4 Summary of literature review

In the beginning of the literature review it was decided to investigate four main questions. The first two questions need to be answered and summarized together since the speed if the vehicle greatly influenced whether the measured values deviated between the EVs and ICEVs. The EVs were found at the lower speeds ranging from 10 km/h up to approximately 50 km/h to emit lower noise levels for all studies. The difference was at around 5 to 10 dBA at 10 km/h and already at 20 km/h it could be seen for some studies to decrease to only a few decibel. The deviations decreased with an increasing speed resulting in the same noise level from both vehicle types with one exception which was the master thesis from the Technical University of Denmark.

Even though it can be seen that there is a difference between the EVs and the ICEVs, it is not at a precise speed where it can be concluded that the vehicles emits the same noise as a function of the dominating tyre/road noise. It seems that many of the studies are based at a smaller number of vehicles which makes it hard to compare the different results. Therefore a need for a broader investigation with a higher number of vehicles can help to give input in the research and see if these findings reoccur with a larger vehicle pool.

The comparison of the spectra between the different vehicles in the research showed that the largest deviations occurs when the vehicles drove slower. The spectra of the EVs there had overall lower levels over the whole frequency range. This is not surprising since it was seen that the overall noise level deviated in the same speed range. As for the higher speeds it is seen that the spectra are closely similar which can be related to the tyre/road being the dominant noise source. It is not possible to determine how the spectra for EVs deviate to those from ICEVs generally since the research depends in many cases on just a few selected vehicles.

Relatively little research was found where psychoacoustic parameters had been used to analyse road traffic noise and especially within the topic of this report. That validates the need to further investigate this to see if this can help to evaluate how noise should be analysed and how it is perceived.

4

Method

Measurements of single pass-by events were captured in combination with a listening test to find out whether there is a difference between the noise emission from ICEVs and EVs and how the noise is perceived. There was in total 282 pass-by measurements distributed even over the 5 different speed limits between 15 km/h, 30 km/h, 40 km/h, 50 km/h and 60 km/h. In the listening test participants were asked to rate the annoyance of representative recordings from each speed limit which were chosen. In total 20 people participated. This section aims to present how the measurements were carried out, which equipment that was used and how the listening test was designed and performed. The A-weighted maximum SPL and the equivalent SPL were calculated later from the measurements by the software ArtemiS SUITE 13.6 in addition with psychoacoustic parameters. From equation 2.3 the L_{AE} was calculated from L_{Aeq}. In addition the equivalent SPL was converted to L_W by equation 2.4 to independently compare the measurements from different distances and to compare it to the CNOSSOS-EU source model.

4.1 Measurement standard ISO 362-1:2022

The method for the measurement was based upon the international measurement standard ISO 362-1:2022 which is an engineering method implemented when measuring noise from vehicles of category M and N in urban traffic. The preconditions and requirements are described in detailed, both for the vehicle under test and the test site itself in the standard. Highlighted requirements of the test site is that it is important that it is relatively flat, the test track and surrounding surfaces should be dry and free from absorbing materials such as powdery snow. There should be no big reflecting objects as fences, buildings or rocks within a radius of 50 m from the test track. The microphone shall be placed 1.2 m above the ground and 7.5 m from the middle of the drive line of the vehicle. The measurement should be made when the temperature ranges from 5°C to 40°C. When measuring below 5°C it is expected to yield higher measurements results due to the effect of the harder rubber. The wind speed shall not exceed 5 m/s during the measurement including wind gusts. The background noise shall be at least 10 dB below the maximum A-weighted SPL recorded of the vehicle but preferably 15 dBA[31].

4.2 Measurement 1

Measurements were performed at two periods during the spring of 2023. The first period of measurements took place between 2023/02/28-2023/03/03. It could be concluded after reviewing the measurements that there was a need for more measurements for the two lowest speed. Additionally measurements were carried out 2023/04/12. In total 282 measurements were collected of vehicles passing at the different locations. The measurements were made south of Oslo at five different roads where the speed limits ranged between 15 km/h and 60 km/h. The measurements from 15 km/h to 50 km/h were measured at Skoglia in Langhus and marked in figure 4.1.

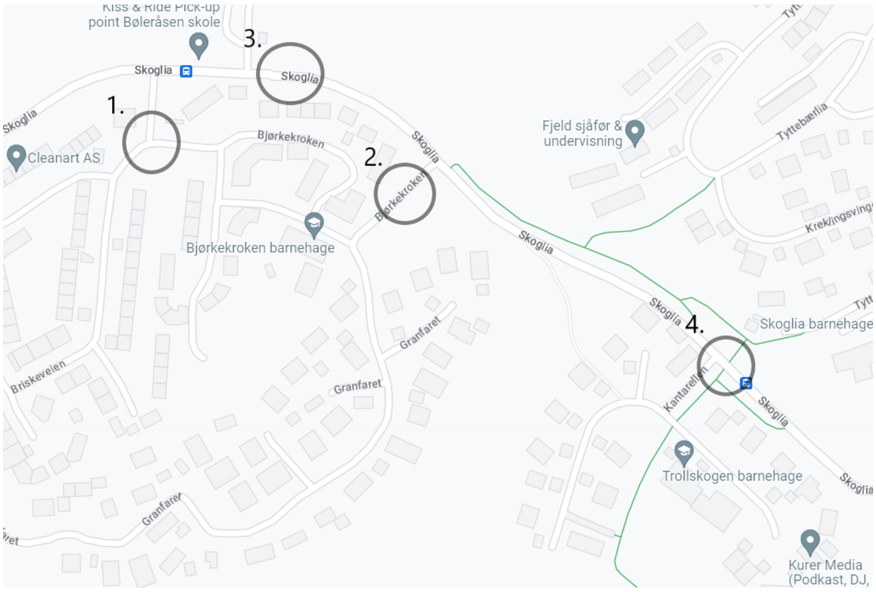


Figure 4.1: Locations of measurements in Skoglia. Number 1 = 15 km/h, 2 = 30 km/h, 3 = 40 km/h and 4 = 50 km/h

The measurements of vehicles driving at a road with the speed limit of 60 km/h was made in Siggerud and is marked in figure 4.2. More detailed descriptions of each measurement are presented further below.

Figure 4.2: Location of measurement in Siggerud. The speed limit of the road was 60 km/h.

4.2.1 Equipment list

During the first measurements between 2023/02/28-2023/03/03 following equipment was used:

- Sound level calibrator B&K Type 4231
- SQuadriga II Serial number 3320
- Microphone set GRAS46AE Serial number 266269 and preamplifier 26CA Serial number 259983
- Microphone set GRAS46AE Serial number 266189 and preamplifier 26CA Serial number 260058
- Microphone set GRAS46AE Serial number 266253 and preamplifier 26CA Serial number 260054
- B&K Artificial head Serial number 33221268

4.2.2 Location 1, 15 km/h,2023-03-03

The measurement of vehicles at the speed limit of 15 km/h took place at the intersection between Briskeveien and Bjørkekroken seen in figure 4.1. The measurement took place approximately between 8.00-10.00. It was a cloudy but still morning. The wind speed was around 1 m/s and the temperature was around 0°C according to the local weather reports. There was no precipitation but hard packed snow covered parts of the ground at the side of the road since before. There was no snow at the road. The setup of the equipment for this location are seen in figure 4.3. For this measurement microphone 3 which normally was placed at the ground was not used. Only recordings from microphone 1, microphone 2 and the artificial head was captured. A total of 8 measurements were made and three of them captured EVs. The drive line of the vehicles from both directions were assumed to be in the middle of the road since it was relative narrow and vehicles passing drove in the middle. Thus the assumption of equal distance to the source independent of the direction is established for this location. The height of microphone 1 and the artificial head was 1 m and for microphone 2 the height was 1.2 m. The distance to the source was 2.6 m for microphone 1 and the artificial head and 4.6 m for microphone 2.

Figure 4.3: Set up of the equipment at location 1.

4.2.3 Location 2, 30 km/h, 2023-03-02

The measurement at location 2 was located at Bjørkekroken seen in figure 4.1. The measurement was carried out during the morning between 08.00-10.00. It was a bright and clear day with no clouds in the sky. The temperature was around 0°C and the speed of the wind was 1 m/s according to local weather reports. The ground was covered partly with hard packed snow at some areas but the road was clear. A total of eight useful measurements was done whereas six of them were of EVs. The vehicles came from two directions heading southwest or northeast. In table 4.1 the distance from each microphone to the source of each direction is seen.

Figure 4.4: Set up of the equipment at location 2.

Table 4.1: Distance between source and microphone at location 2. The compass point indicates which direction the car is driving towards.

Microphone	**Distance to source southwest [m]**	**Distance to source northeast [m]**
Artificial head	5.0	2.0
Microphone 1	5.0	2.0
Microphone 2	6.8	3.8
Microphone 3	6.8	3.8

4.2.4 Location 3, 40 km/h, 2023-02-28

The measurement at location 3 was located after the pedestrian crossing at Skoglia marked in figure 4.1. It took place between 10.00-13.00. It was a sunny, clear and still day. The temperature was around 2°C and the wind speed was around 2 m/s according to local weather reports. The set up of the equipment can be seen in figure 4.5. The road was approximately 7 m wide and the vehicles drove either in the eastern or western direction. The passages marked east were closest to the measurement equipment. The distances to the source in the middle of each traffic lane is seen in table 4.2

Figure 4.5: Set up of the equipment at location 3.

Table 4.2: Distance between source and microphone at location 3. The compass point indicates which direction the car is driving towards.

Microphone	**Distance to source east [m]**	**Distance to source west [m]**
Artificial head	5.75	9.25
Microphone 1	5.75	9.25
Microphone 2	8.25	11.75
Microphone 3	8.25	11.75

4.2.5 Location 4, 50 km/h, 2023-03-01

The measurement at the fourth location took place in Skoglia and was carried out between 9.00-12.30. The location of this measurement is seen in 4.1 and was placed around 15 meters before the bus stop. It was a sunny day without clouds and the temperature was around 3 °C. The speed of the wind was 1 m/s according to local weather reports. The set up of the equipment is presented in figure 4.6 and the distances of each microphone to the source is found in 4.3.

Figure 4.6: Set up of the equipment at location 4.

Table 4.3: Distance between source and microphone at location 4. The compass point indicates which direction the car is driving towards.

Microphone	**Distance to source northwest [m]**	**Distance to southeast [m]**
Artificial head	5.0	9.0
Microphone 1	5.0	9.0
Microphone 2	7.25	11.25
Microphone 3	7.25	1125

4.2.6 Location 5, 60 km/h, 2023-03-02

The fifth measurement took place along Siggerudveien between approximately 12.00-15.00. It was a clear day with some clouds in the sky. The temperature was around 7 °C and the wind speed was around 2 m/s according to the local weather reports. The equipment was placed as in figure 4.7 and the distances from the source to the different microphones are seen in table 4.4.

Figure 4.7: Set up of the equipment at location 5.

Table 4.4: Distance between source and microphone at location 5. The compass point indicates which direction the car is driving towards.

Microphone	**Distance to source south [m]**	**Distance to north [m]**
Artificial head	6.4	9.4
Microphone 1	6.4	6.4
Microphone 2	8.1	11.1
Microphone 3	8.1	11.1

4.3 Measurement 2

The second measurement took place between 2023-04-14 and 2023-04-14 since the data collected from location 1 and 2 from measurement 1 were insufficient. Additionally 70 recordings together were captured from location 1 and 2 seen in figure 4.1. No recordings with the artificial head were made during the measurement session.

4.3.1 Equipment

During the second measurement following equipment was used:

- Sound level calibrator NOR1255 Serial number 125525677
- SQuadriga III Serial number 33240107
- Microphone set GRAS 46AE Serial number 442867
- Microphone set GRAS 46AE Serial number 442868
- Microphone set GRAS 46AE Serial number 442869

4.3.2 Location 1, 15 km/h,2023-04-13

The second measurement at location 1 took place between 13.00-17.00. It was relative cloudy during the measurement but without precipitation. The wind speed was about 3 m/s and the temperature around 10°C according to the local weather reports. The equipment was placed at the same position as the previous measurement. A set up of the equipment is seen in figure 4.8.

Figure 4.8: Set up of equipment at location 1 during second measurement.

4.3.3 Location 2, 30 km/h,2023-04-14

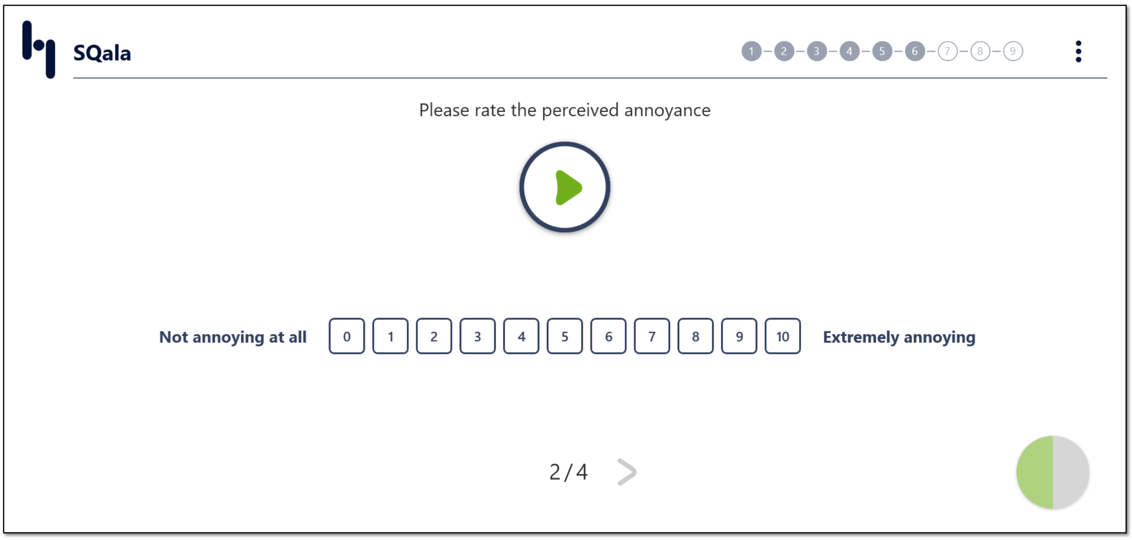
The second measurement took place between 08.00-12.00 at location 2. Clouds covered the sky and the temperature was around 5 to 7 °C. The wind speed was around 2 m/s according the the local weather reports. The equipment was placed at the same distances as in table 4.1 and the set up is seen in figure 4.9.

Figure 4.9: Set up of equipment at location 2 during second measurement.

4.4 Listening test

A listening test was conducted at the Division of Applied Acoustic at Chalmers University of Technology during April 2023. The listening test was designed in the software ArtemiS Suite 13.6. There was a total of 20 people participating in the listening test. Out of the 20 people 7 were females and 13 were males. There was no compensation for participating in the listening test. The listening test took place during two days where each session was around 15 to 20 minutes and at most 4 participants at the same time.

There are several different variations of listening test available, thus the objective and purpose of the listening test needs to determine which method that is used. For this listening test a method called category judgement was used. Each participant is presented with the sound samples chosen one at a time with the possibility to replay the sound once. The participants were then asked to rate the sound samples depending of how annoying it was perceived. For this listening test a 11 point scale was used ranging from 0 to 10 where 0 represented "Not annoying at all" and 10 represented "Extremely annoying". The whole listening test was composed of 20 sound stimuli, 4 stimuli for each speed limit where 2 were EV and 2 were ICEV. The used stimuli for the listening test were chosen to represent the average sound stimuli for each category. The length of each sound stimuli were around 10 seconds. In figure 4.10 the design of listening test in ArtemiS can be seen.



Please rate the perceived annoyance

Figure 4.10: Visualization of participants interface in the listening test.

4.5 Post-processing of data and statistical analysis

From the measurement ArtemiS Suite 13.6 was used to receive the L_{Aeq},L_{Amax} and the psychoacoustic parameters. Matlab version R2022b was used to manage all the data, calculations of L_{AE}, L_{WA} and PA, together with the visualization of all plots. Statistical calculations were made with statistical software R version 4.2.2 with the interface R Commander. The statistical analysis is a multivariate linear regression used in earlier work by Sigmund Olafsen and Atle Stensland where investigations of the tram noise in Oslo were evaluated [6]. Categorical variables were used for the age of the vehicle and the speed limit whereas continuous dependent variables were used for the weight of the vehicle and transformed into a logarithmic scale. Statistical analysis was also made for the engine power of each vehicle and the different distances from 2.0 m to 11.75 m as a logarithmic variable but are not presented in this report.

5

Results

The results from the measurements and listening test are presented here. The mean values of the calculated third octave bands for each driving direction and microphone 1 and 2 are shown. The background noise is evaluated and the sound power levels calculated from the measurements are compared with the CNOSSOS-EU source model.

5.1 Background noise

The background noise was measured at each location and the single number value of the energy mean equivalent SPL are seen in table 5.1. The single value of the background noise can be seen to be more then 20 dBA lower then the measurements of the vehicles which fulfills the requirement of 10 dBA required by the ISO 362-1:2022 standard. In appendix A.3 to A.7 the individual comparison for each speed limit is seen. All of the vehicle measurements are compared to the energy mean of the background noise to see for which third-octave bands the signal to noise ratio is acceptable. A difference of 6 dBA is accepted as a threshold which yields a results of +1 dBA for the results. At location 1 at 15 km/h seen in appendix A.3 the results below 80 Hz should be considered carefully. At location 2 and 3 seen in appendix A.4 and A.5 results below 160 Hz falls under this threshold. Location 4 at 50 km/h seen in appendix A.6 requires cautions when treating results below 100 Hz. At last results seen in appendix A.7 from 60 km/h shows that results below 63 Hz falls below the threshold boundary.

Table 5.1: Single number value of L_{Aeq} from background noise compared to each locations and its belonging speed limit. The single number value is an energy mean value.

Speed limit	Background noise [dBA]	Vehicles mic1 [dBA]	Vehicles mic 2 [dBA]
15 km/h	41.0	63.5	61.2
30 km/h	40.1	62.6	61.2
40 km/h	42.0	59.2	57.0
50 km/h	39.2	60.5	58.8
60 km/h	37.6	66.2	65.1

5.2 Results from 15 km/h

The arithmetic mean value of L_{AE} calculated from the measurements for both microphone 1 and 2 are presented in figure 5.1. In appendix A.8 and A.9 the individual results for each microphone and direction is presented together with its 95% CI. The continuous and dotted red lines mark the ICEVs in all figures to come. The EVs are presented by the black continuous and dotted lines. The ICEVs can be seen to have higher values for all frequencies except around 160 Hz. The difference is around only a few decibel for each third octave band and the single number value deviates between 1.8 and 1.9 dB at 15 km/h as seen in table 5.2 and 5.3.

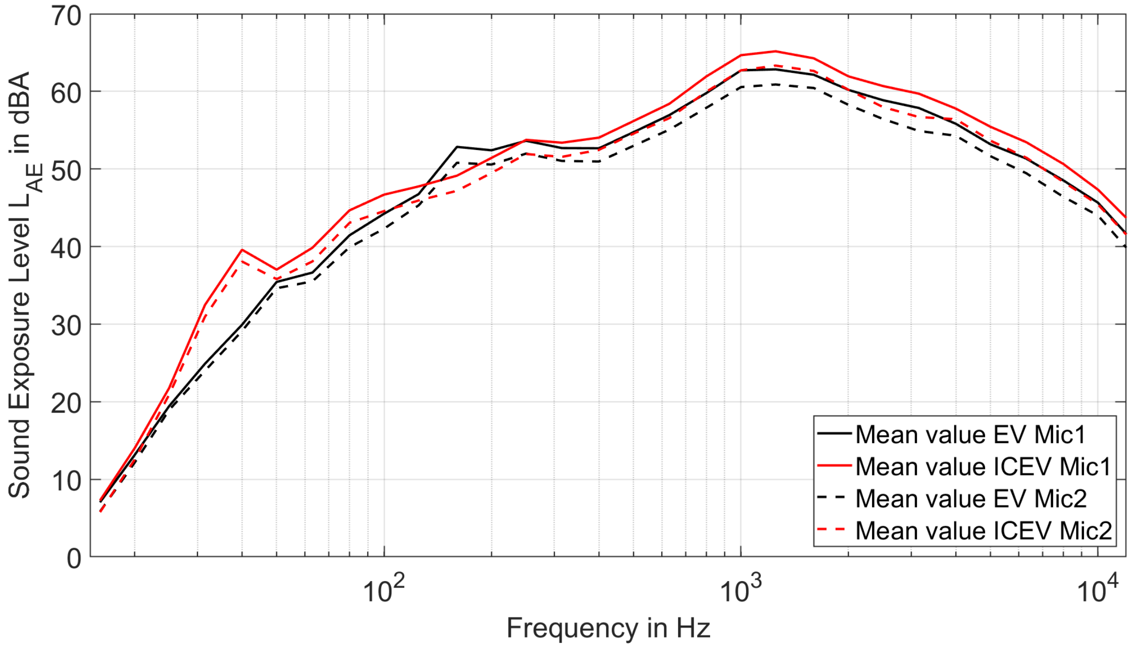


Figure 5.1: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 15 km/h and for microphone 1 and 2.

The arithmetic mean values of the maximum SPL measured at microphone 1 and 2 are presented in figure 5.2. The individual results and its CI are seen in appendix A.10 and A.11. The ICEVs are seen to be around 2 to 4 dBA higher then the EVs except for the frequencies around 160 Hz. The single number of the ICEVs are measured to be 2.1 to 2.2 dBA higher then the EVs.

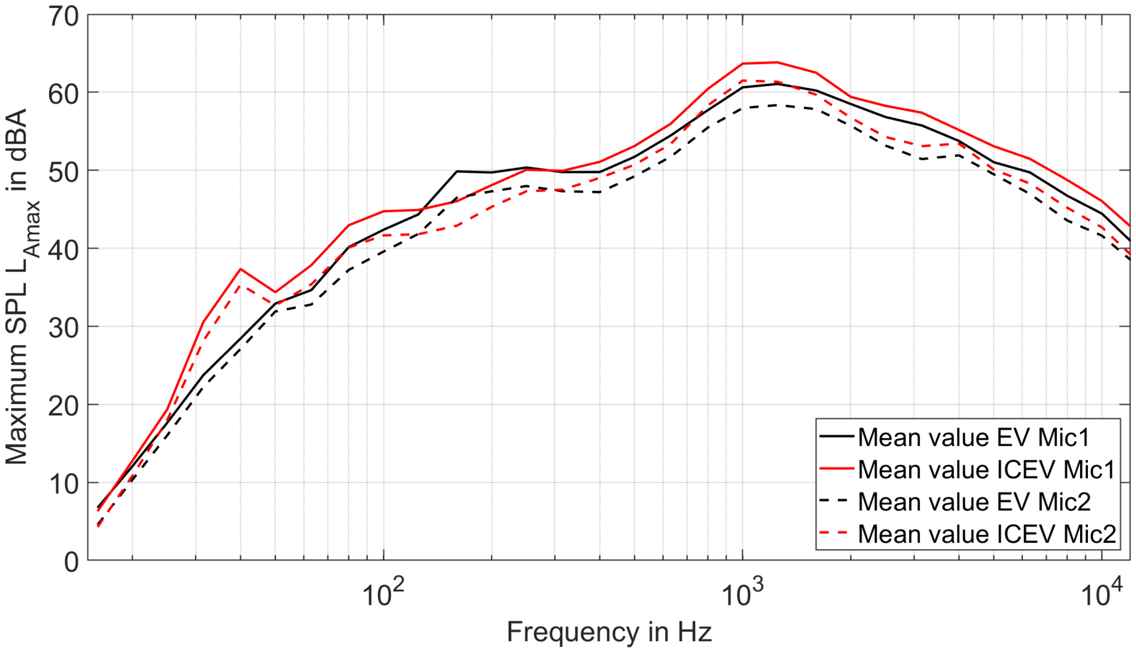


Figure 5.2: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 15 km/h and for microphone 1 and 2.

Table 5.2: Single number values from microphone 1 at 15 km/h

Vehicle type	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	71.0	±2.7	69.3	±3.0
ICEV	72.8	±1.5	71.4	±1.7

Table 5.3: Single number values from microphone 2 at 15 km/h

Vehicle type	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	69.0	±2.5	66.6	±2.5
ICEV	70.9	±1.4	68.8	±1.6

5.3 Results from 30km/h

The arithmetic mean value of L_{AE} is seen in figure 5.3 and 5.4. The individual results are seen in appendix A.12 to A.15. The deviations between the different vehicles can be seen in the lower frequency range where the ICEVs emit more noise. Most of these deviations are in the frequency range under 160 Hz where the background noise was lower than 6 dBA, thus treated with caution. From 200 Hz and above the noise emission from the vehicles for each third octave band are relative similar. This trend can be seen for both directions.

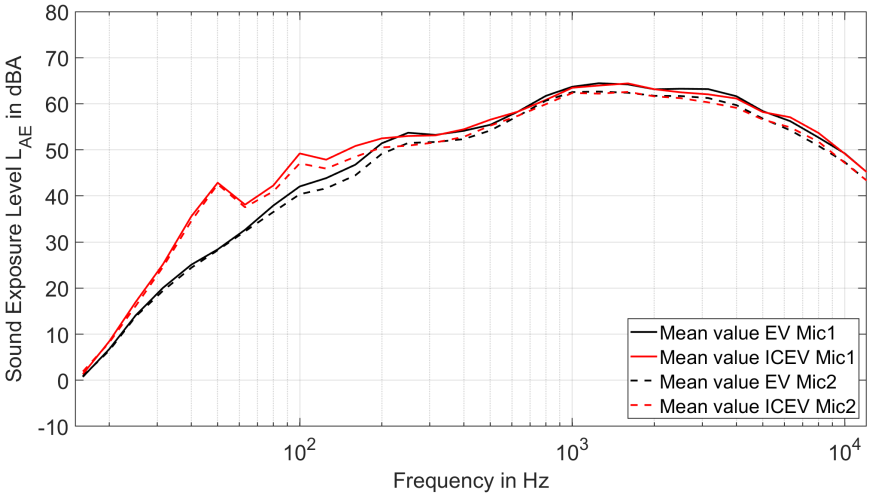


Figure 5.3: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 30 km/h and for microphone 1 and 2 in the northeast direction.

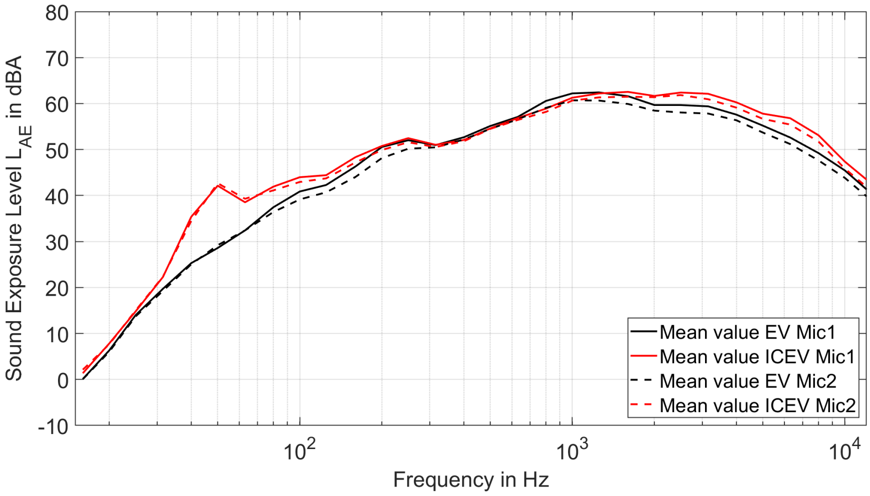


Figure 5.4: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 30 km/h and for microphone 1 and 2 in the southwest direction

The arithmetic mean maximum SPL for both direction is presented in figure 5.5 and 5.6. The individual results and CI are seen in appendix A.16 to A.19. The same trend is seen as for L_{AE} whereas the deviations are present in the lower frequencies in figure 5.5. The ICEVs have maximum levels around 2 to 3 dBA higher in that frequency range for the northeast direction. For the southwest direction the small difference in this frequency range makes it negligible.

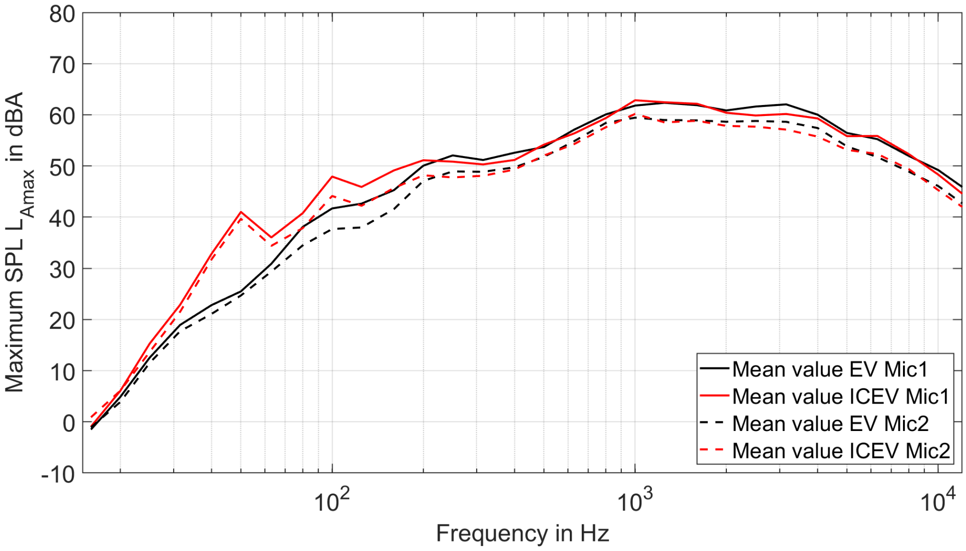


Figure 5.5: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 30 km/h and for microphone 1 and 2 in the northeast direction.

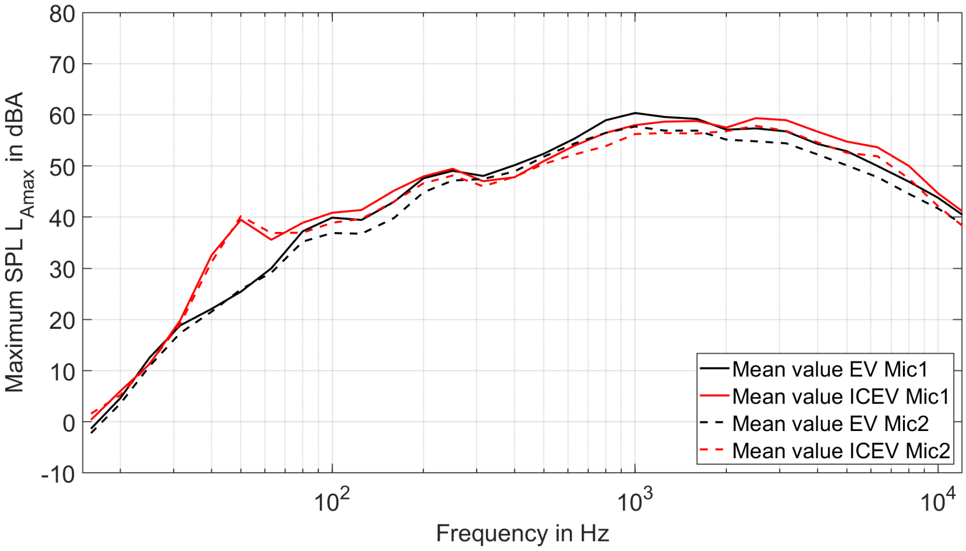


Figure 5.6: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 30 km/h and for microphone 1 and 2 in the southwest direction.

The differences between the arithmetic mean single values of the SEL are not greater then 0.8 dBA seen in table 5.4 and 5.4. The same trend is seen for the arithmetic mean value of the single number of the maximum SPL. The difference between ICEV and EV is not greater then 0.3 dBA seen in table 5.4 and 5.4.

Table 5.4: Single number values from microphone 1 at 30 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	Northeast	73.5	1.1	71.8	1.2
ICEV	Northeast	73.3	1.9	71.7	2.2
EV	Southwest	71.1	1.5	69.1	2.4
ICEV	Southwest	71.9	3.5	68.8	4.3

Table 5.5: Single number values from microphone 2 at 30 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	Northeast	72.0	1.1	69.1	1.1
ICEV	Northeast	71.6	1.9	68.8	2.1
EV	Southwest	69.6	1.3	66.7	1.8
ICEV	Southwest	71.1	3.4	66.9	3.8

5.4 Results from 40 km/h

The arithmetic mean L_{EAE} both direction are presented in figure 5.7 and 5.8. Individual results are seen in appendix A.20 to A.23. For all third octave bands except around 200 Hz the ICEVs are higher thus the deviations are largest under 200 Hz. The deviation are not more than approximately 2 dBA which is not a significant difference. A first peak seems to occur after 200 Hz for both vehicle types follow by a second one around 1000 Hz.

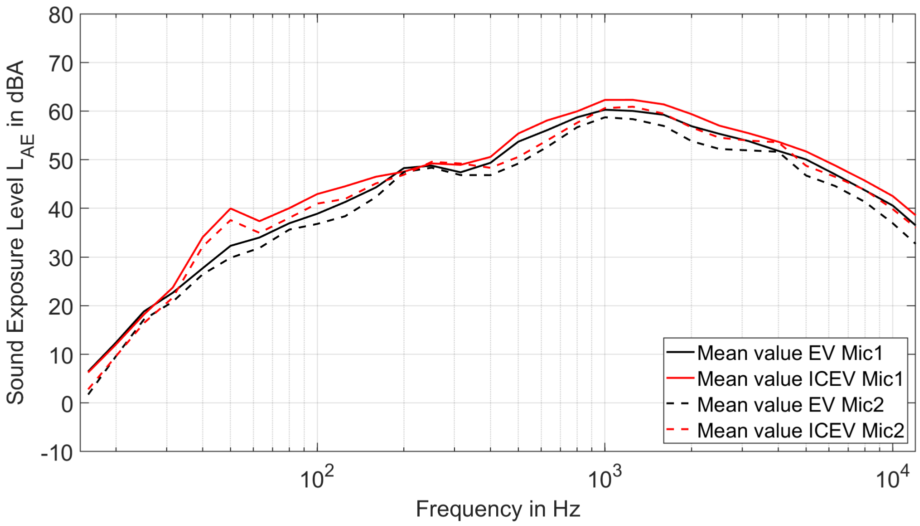


Figure 5.7: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 40 km/h and for microphone 1 and 2 in the eastern direction

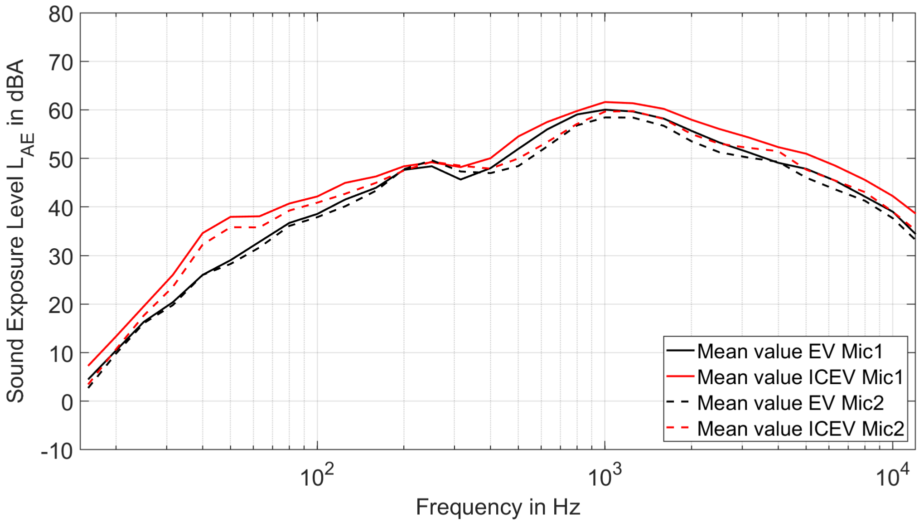


Figure 5.8: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 40 km/h and for microphone 1 and 2 in the western direction

In figure 5.9 and 5.10 the arithmetic mean value of L_{Amax} is presented for both directions. The individual results and its CI are seen in appendix A.24 to A.27. The ICEVs emits higher levels around almost every third octave band. The exceptions is around 200 Hz where the EVs have a higher level in the western direction. After 200 Hz the differences are relative small up to approximately 3 dBA at most. The peaks around 200 Hz and 1000 Hz are harder to distinguish but can be observed.

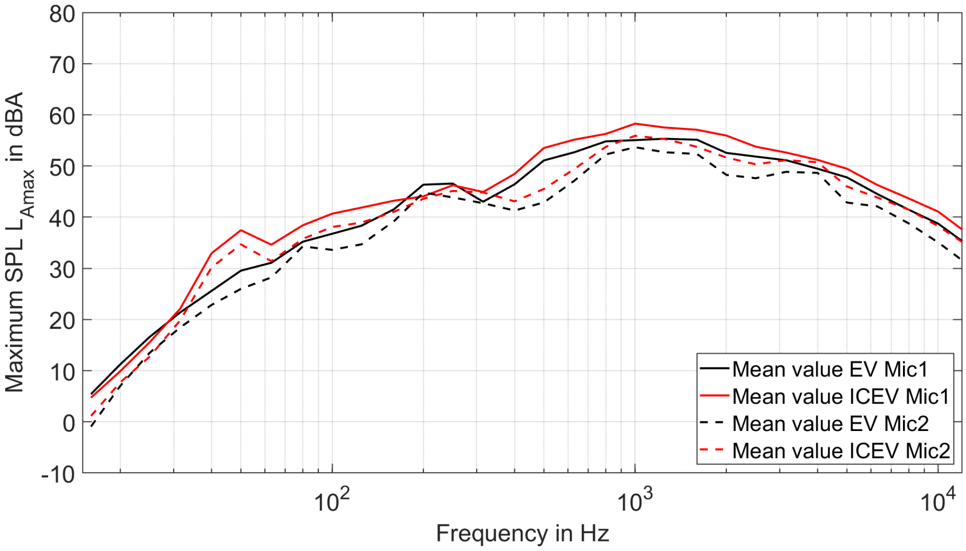


Figure 5.9: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 40 km/h and for microphone 1 and 2 in the eastern direction.

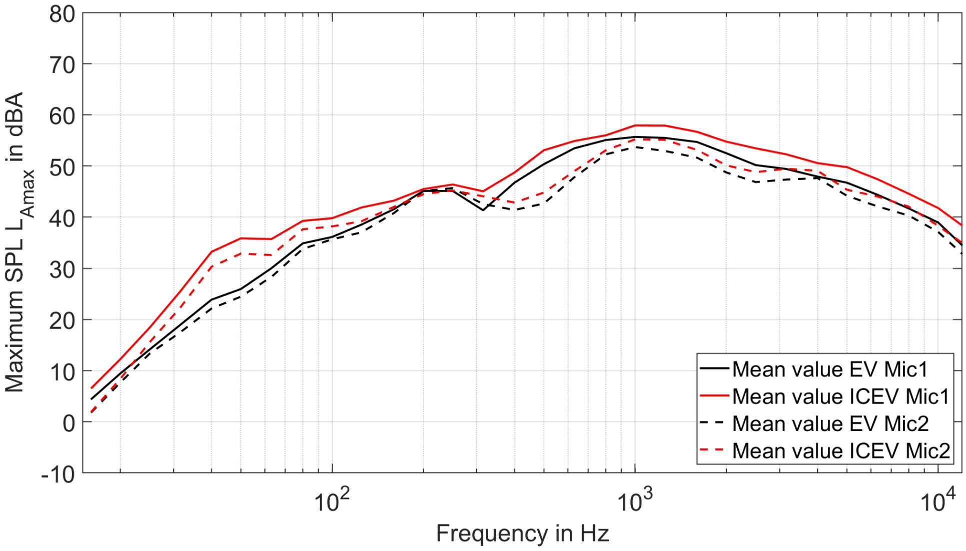


Figure 5.10: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 40 km/h and for microphone 1 and 2 in the western direction.

The arithmetic mean single value of L_{AE} and L_{Amax} together with its CI is presented in table 5.6 and 5.7. The ICEVs have between 1.2 to 2.0 dBA higher levels then EVs for L_{AE}. The same trend is seen for L_{Amax} whereas the difference is 1.5 to 2.0 dBA higher.

Table 5.6: Single number values from microphone 1 at 40 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	East	68.1	1.8	64.4	2.0
ICEV	East	70.0	1.7	66.7	2.0
EV	West	67.4	1.3	64.3	1.7
ICEV	West	69.3	1.1	66.6	1.3

Table 5.7: Single number values from microphone 2 at 40 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	East	66.0	1.7	61.5	1.6
ICEV	East	68.0	1.7	63.8	2.0
EV	West	65.8	1.3	61.7	1.6
ICEV	West	67.0	1.1	63.2	1.2

5.5 Results from 50 km/h

In the measurement in the northwestern direction the largest deviations between EV and ICEV are in the lower frequencies where EV emits less noise seen in 5.11. After 200 Hz the deviations in L_{AE} between the vehicle types are 1 to 2 dBA. Results under 100 Hz should be treated carefully because of the background noise. Noteworthy is that EV emits higher values than ICEV after 2000 Hz but it is still in the range of 1 to 2 dBA.

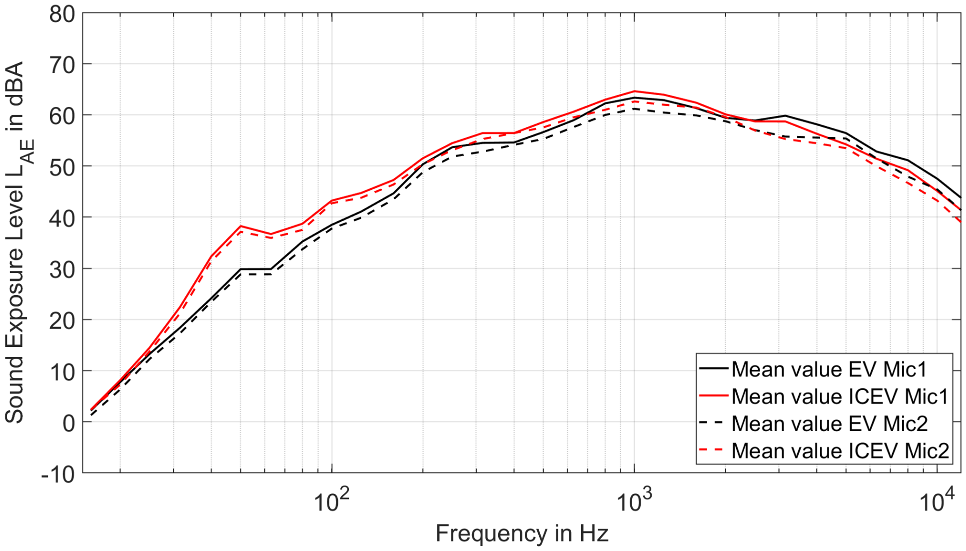


Figure 5.11: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 50 km/h and for microphone 1 and 2 in the northwestern direction

The same trend can be seen for L_{AE} in figure 5.12 for the southeastern direction but with a larger difference in the higher frequencies whereas the EVs are quieter than ICEVs compared to the northwestern direction. The individual results and its CI are seen in appendix A.28 to A.31 for both microphones and directions.

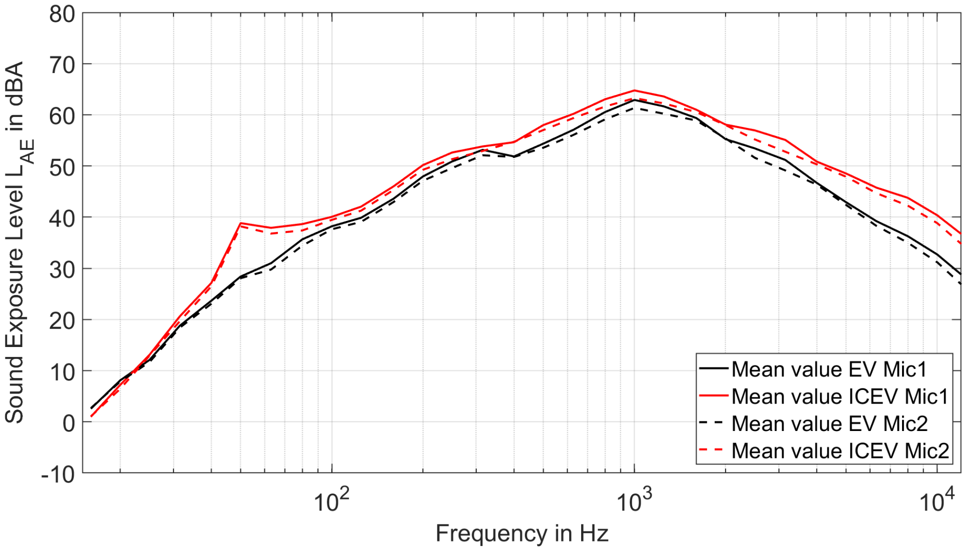


Figure 5.12: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 50 km/h and for microphone 1 and 2 in the southeastern direction

In figure 5.13 the maximum SPL is seen for 50 km/h in the northwestern direction. EVs emits lower levels up until 2000 Hz compared to ICEVs. The largest deviation is seen in the lower frequencies under 100 Hz whereas the background noise influences the results certainty.

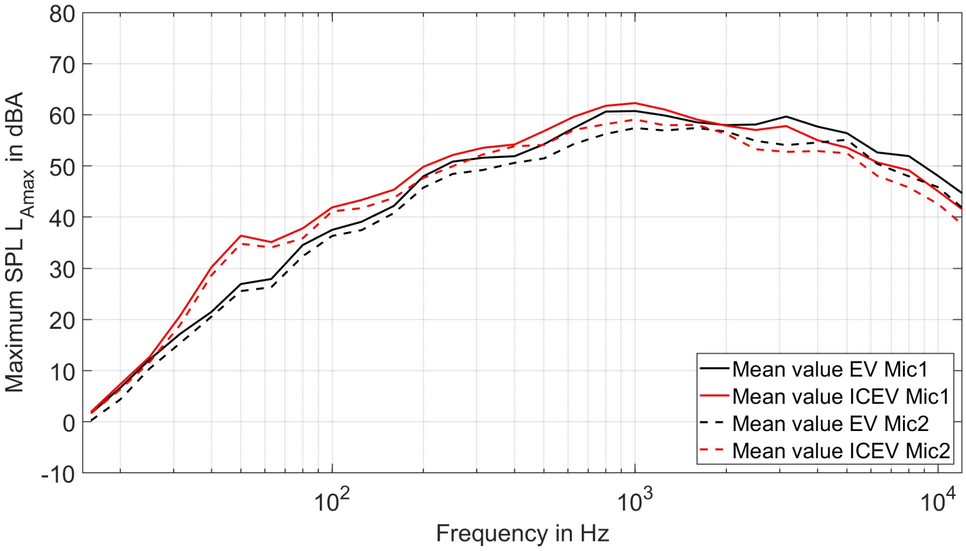


Figure 5.13: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 50 km/h and for microphone 1 and 2 in the northwestern direction.

The maximum SPL in the southeastern direction is seen in figure 5.14. In the frequency range between 100 Hz and 2000 Hz EVs emits up to 3 dBA less then ICEVs. In the higher frequencies this deviations increases to up around 5 dBA. The individual results and the CI are seen in appendix A.32 to A.35.

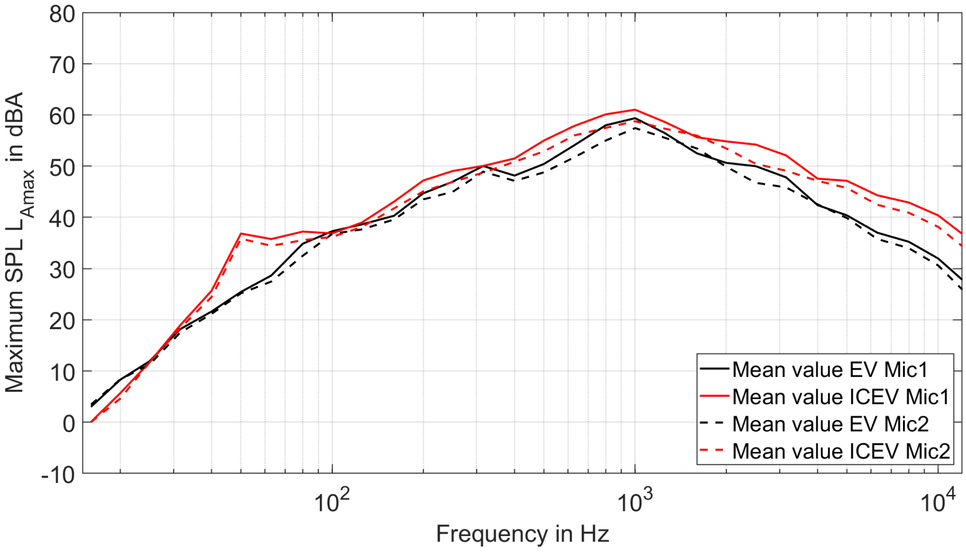


Figure 5.14: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 50 km/h and for microphone 1 and 2 in the southeastern direction.

The arithmetic mean calculated from the single number value of L_{AE} and L_{Amax} for both microphones and directions are seen in table 5.8 and 5.9. The differences between EVs and ICEVs are within 1 dBA for the northwest direction for both microphone 1 and 2. The same trend can be seen in the southwest direction where EV are 2.3 to 2.4 dBA lower but with higher CI for the results.

Table 5.8: Single number values from microphone 1 at 50 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	Northwest	71.6	1.3	70.1	1.8
ICEV	Northwest	72.3	0.9	70.4	1.2
EV	Southeast	69.0	2.7	65.1	2.7
ICEV	Southeast	71.3	2.0	67.8	2.1

Table 5.9: Single number values from microphone 2 at 50 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	Northwest	69.7	1.3	67.3	1.7
ICEV	Northwest	70.7	0.9	67.8	1.2
EV	Southeast	67.8	2.9	63.6	2.7
ICEV	Southeast	70.2	2.0	66.0	2.1

5.6 Results from 60 km/h

At 60 km/h the L_{AE} in the north direction can be seen to be similar for both EVs and ICEVs in the north direction seen in figure 5.15. The only significant deviation can be observed in the lower frequencies which are close to 60 Hz where the threshold influenced by the background noise is. The individual results and CI are seen in appendix A.36 and A.37.

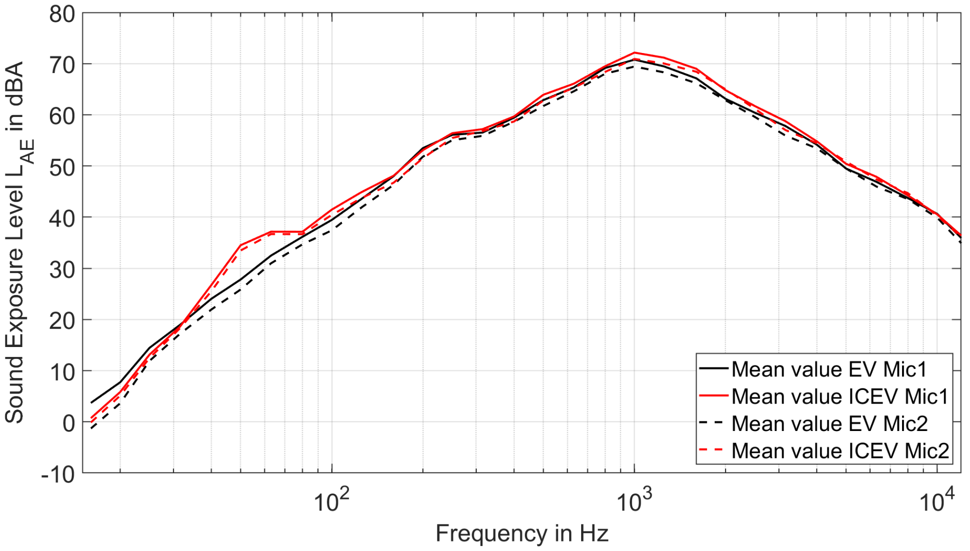


Figure 5.15: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 60 km/h and for microphone 1 and 2 in the northern direction

In the south direction the sound exposure level follows the same trend but with a smaller difference at higher frequencies where EV are 1 to 3 dBA lower seen in figure 5.16. The indivudal results and CI are seen in appendix A.38 and A.39.

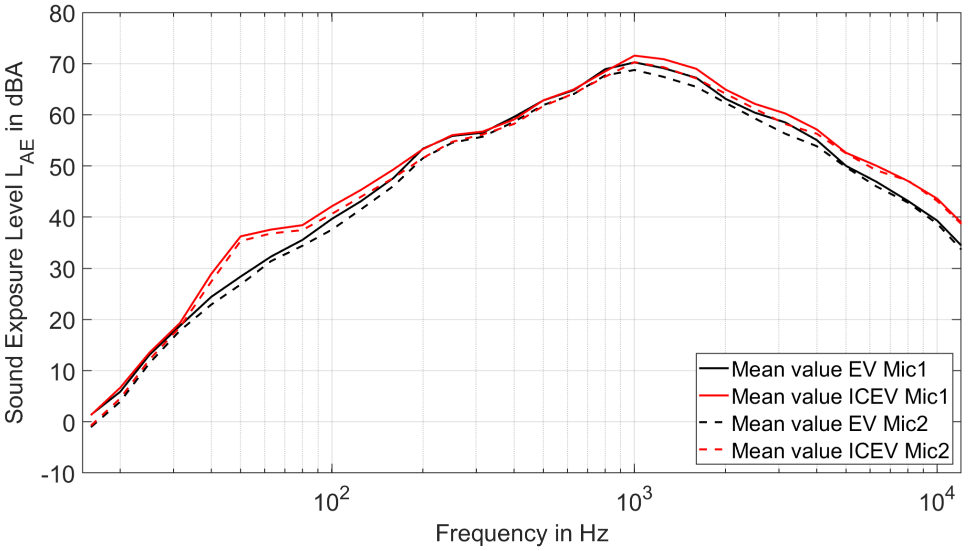


Figure 5.16: Arithmetic mean value of the sound exposure level in third octave bands for EVs and ICEVs. The measurements are from 60 km/h and for microphone 1 and 2 in the northern direction

The maximum SPL in the north direction is seen in figure 5.17. The both curves from EVs and ICEVs follows each other relative closely from 200 Hz and above with small deviations.

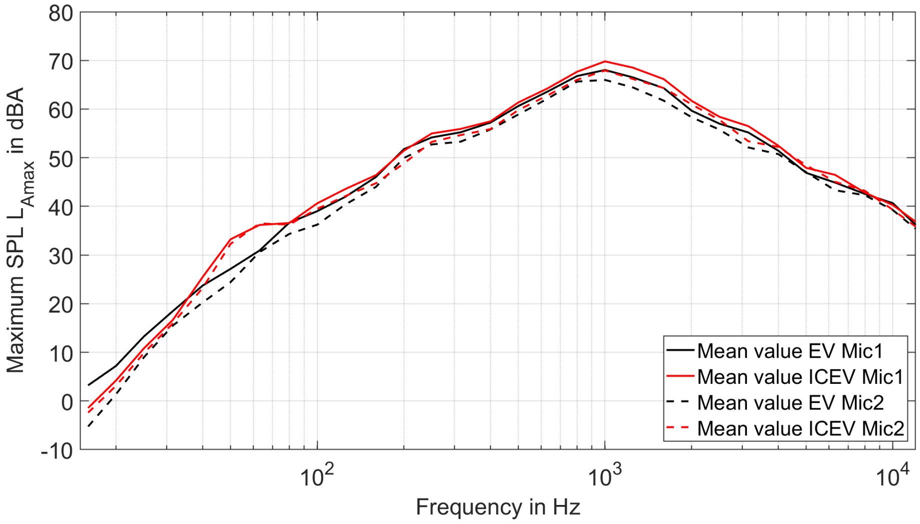


Figure 5.17: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 60 km/h and for microphone 1 and 2 in the north direction.

In the south direction the maximum SPL have small differences between 200 Hz and 1000 Hz for EVs and ICEVs. Outside of this range EVs are seen to have lower values than ICEVs but still in minor range of 1 to 4 dBA. The individual results for each microphone and direction are seen in appendix A.40 to A.43.

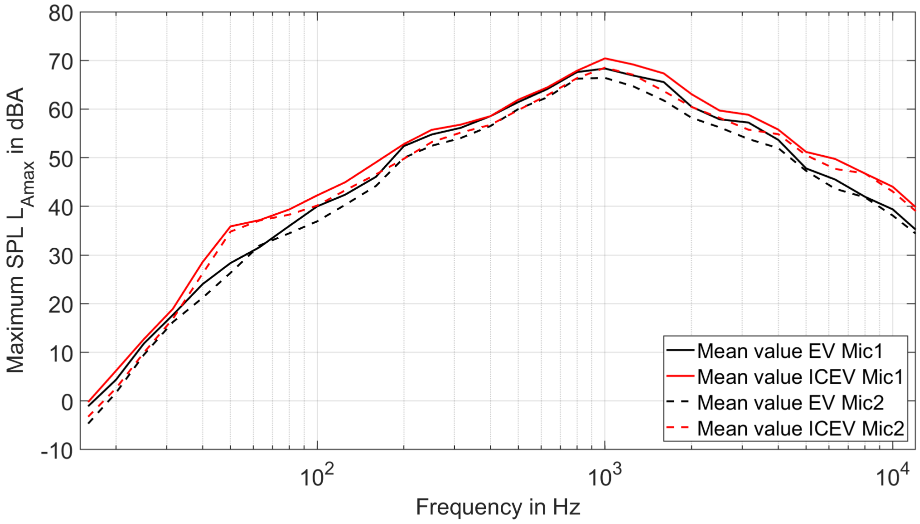


Figure 5.18: Arithmetic mean value of L_{Amax} in third octave bands for EVs and ICEVs. The measurements are from 60 km/h and for microphone 1 and 2 in the south direction.

The arithmetic single mean value of L_{AE} and L_{Amax} for both microphones and directions are seen in table 5.10 and 5.11. The L_{AE} from EVs are 1.1 to 1.3 dBA lower and the maximum SPL is 1.4 to 1.5 dBA lower.

Table 5.10: Single number values from microphone 1 at 60 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	South	76.5	1.7	74.9	1.9
ICEV	South	77.6	1.3	76.4	1.4
EV	North	76.8	2.0	74.2	2.2
ICE	North	78.0	1.5	75.6	1.5

Table 5.11: Single number values from microphone 2 at 60 km/h

Vehicle type	Direction	L_{AE} [dBA]	95% CI for L_{AE} [dBA]	L_{Amax} [dBA]	95% CI for L_{Amax} [dBA]
EV	South	75.2	1.6	72.8	1.7
ICE	South	76.3	1.3	74.3	1.5
EV	North	75.7	2.1	72.5	2.1
ICE	North	77.0	1.5	73.9	1.6

5.7 Sound power and comparison to CNOSSOS-EU

The single number value of calculated energy average sound power from the measurements of EVs and ICEVs are compared to the single number value from the CNOSSOS-EU method. It is seen in table5.12. EVs can be seen to have almost equal or lower levels for all speed compared to ICEVs. The differences between the two vehicle type are at most 1,9 dBA. The single number calculated with CNOSSOS are all higher than for EVs and ICEVs except at 60 km/h.

Table 5.12: Single number value of energy average sound power level for EVs and ICEVs compared to calculated value by CNOSSOS for category 1.

Speed limit [km/h]	L_{WA} for EV [dBA]	L_{WA} for ICEV [dBA]	CNOSSOS [dBA]
15	85.3	85.2	86.2
30	87.8	88.3	90.3
40	90.5	90.4	93.3
50	91.1	93.0	96.0
60	99.6	98.2	98.3

In figure 5.19 a box plot of each vehicle type and speed limit is presented. The red line shows the median value, the top and bottom of the box marks the 75th and 25th percentile. The dotted whiskers extends to the most extreme outliers not defined as outliers. Outliers are marked with red crosses. An outlier is defined to be more than 1.5 times the distance between the bottom and top of the box called the interquartile range. As seen in figure 5.19 at 15 km/h EV have two outliers which if outliers are not included would lower the single number value from 85.3 dBA to 81.2 dBA. The risk with not including outliers is that information of event that has happened is not included and if it has happened once it can happen again.

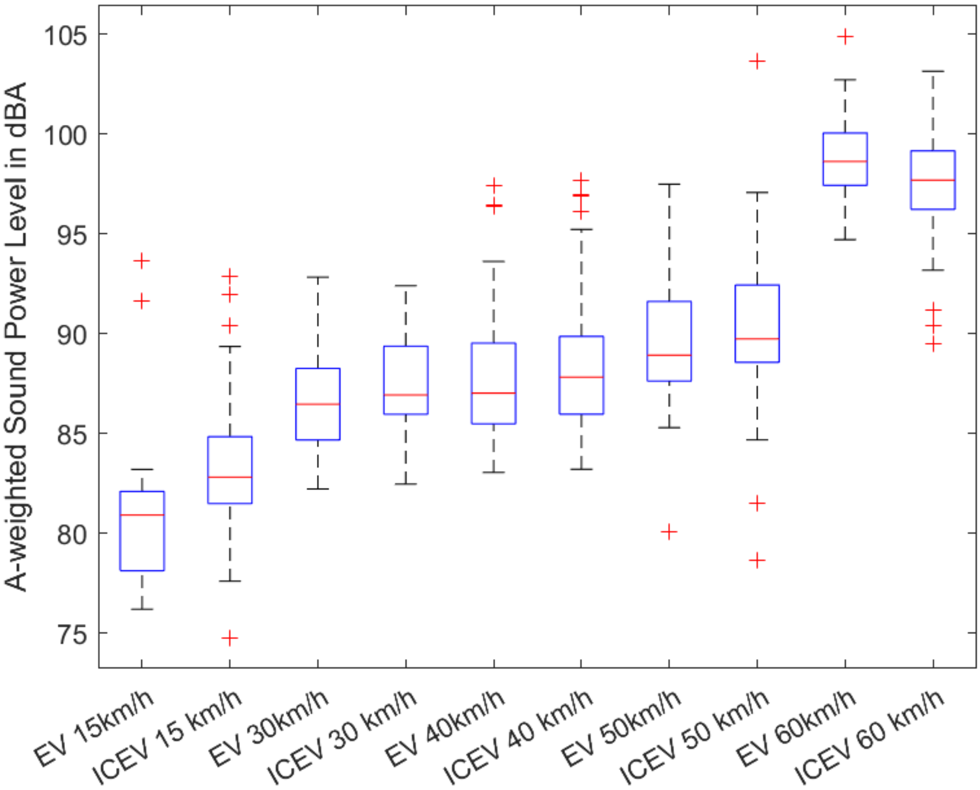


Figure 5.19: Box plot of A-weighted sound power level for each vehicle type and speed limit.

The energy mean value of sound power for each octave band for both vehicle categories were compared to the CNOSSOS-EU method. The comparison at 15 km/h can be seen in figure 5.20. The differences between the vehicle types are low within most of the octave band and at most around 3 dBA. Both EVs and ICEVs are quieter then the calculated level with CNOSSOS except at 1000 Hz.

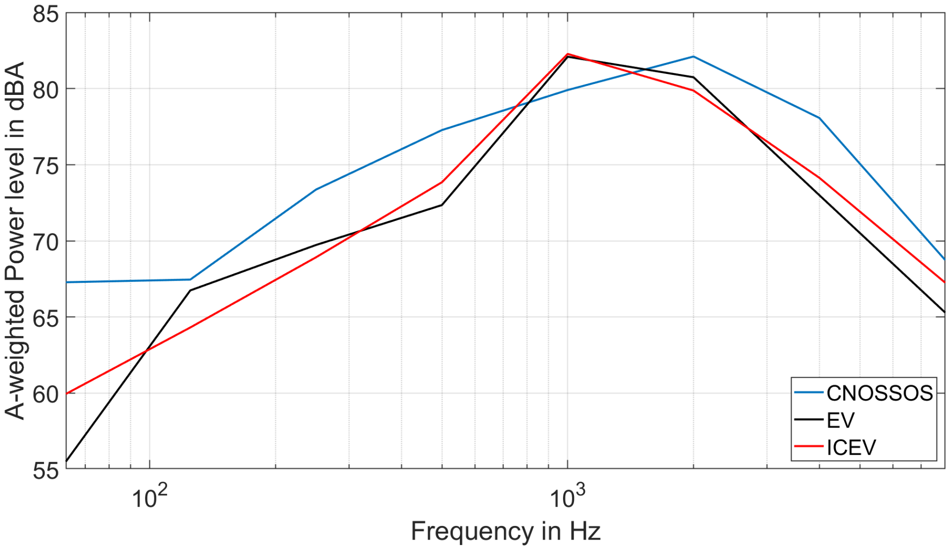


Figure 5.20: Energy average of A-weighted sound power level for each vehicle category compared to CNOSSOS-EU method at 15 km/h in octave bands.

In figure 5.21 the deviation between EVs and ICEVs are almost indistinguishable. The calculated sound power level from CNOSSOS are approximately 3 dBA higher in this range between 200 and 2000 Hz.

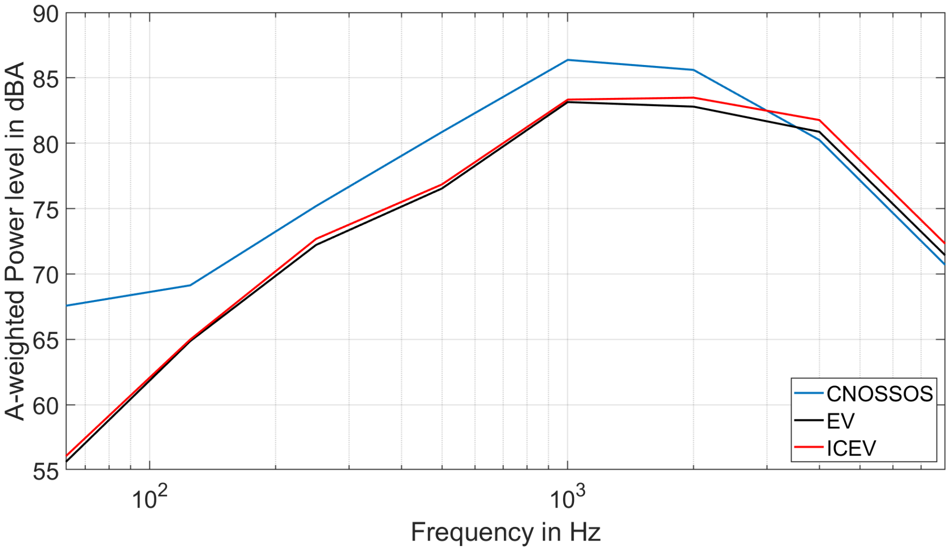


Figure 5.21: Energy average of A-weighted sound power level for each vehicle category compared to CNOSSOS-EU method at 30 km/h in octave bands.

The comparison between EVs and ICEVs with CNOSSOS are seen in figure 5.22 at 40 km/h. The deviations between EVs and ICEVs are again hard to distinguish and follows each other closely. Comparing the octave band of the A-weighted sound power for both vehicle type it is seen that levels calculated from CNOSSOS are 1 to 4 dBA higher from 150 Hz and above.

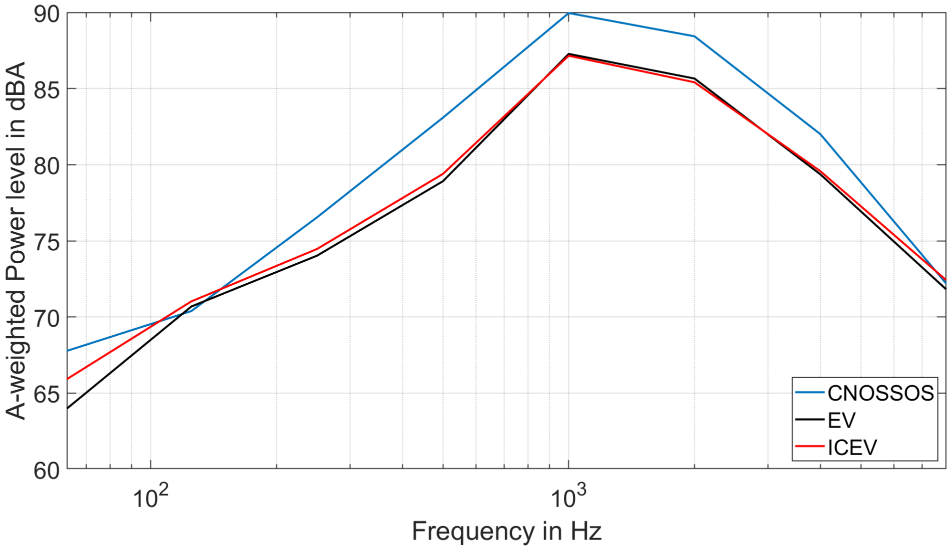


Figure 5.22: Energy average of A-weighted sound power level for each vehicle category compared to CNOSSOS-EU method at 40 km/h in octave bands.

At 50 km/h the comparison of the energy average of A-weighted sound power for both vehicle types and CNOSSOS are seen in figure 5.23. The A-weighted sound power levels from ICEVs are around 2 dBA higher than EVs for all frequencies. Compared to CNOSSOS all levels from EVs and ICEVs falls below the calculated value except at 250 Hz. ICEVs also exceeds the levels from CNOSSOS at the lowest and highest octave band.

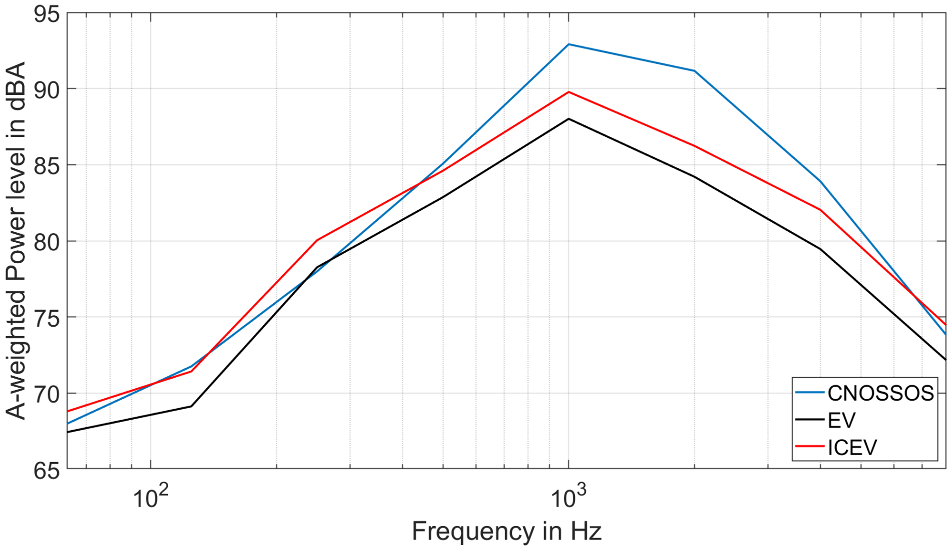


Figure 5.23: Energy average of A-weighted sound power level for each vehicle category compared to CNOSSOS-EU method at 50 km/h in octave bands.

At 60 km/h the energy average of sound power from EVs are seen to be higher in almost the whole frequency range compared to EVs. All though the difference is at most 1.5 dBA. ICEVs and EVs is seen to exceed the levels from CNOSSOS in the frequency range of 200 Hz to 1000 Hz and but approximately follows the same curve structure as CNOSSOS.

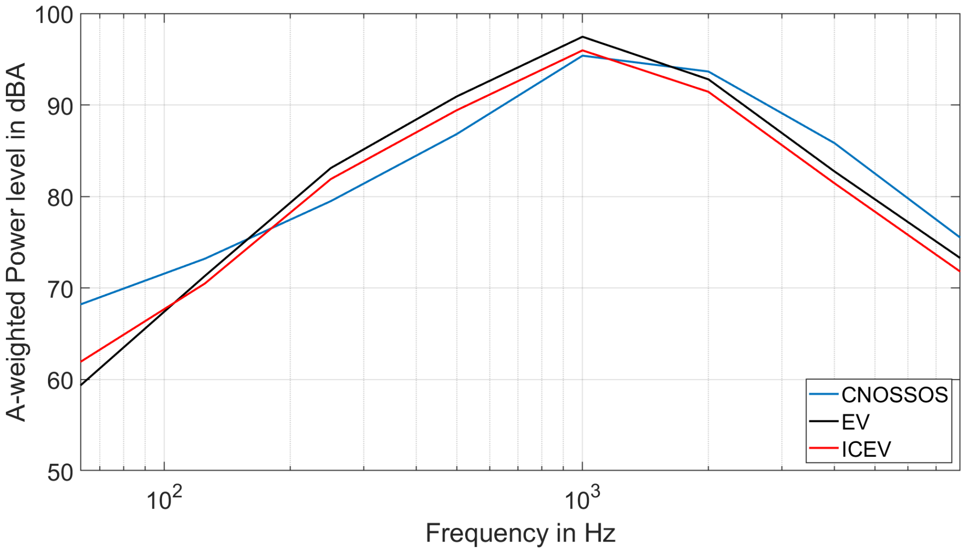


Figure 5.24: Energy average of A-weighted sound power level for each vehicle category compared to CNOSSOS-EU method at 60 km/h in octave bands.

5.8 Psychoacoustics

The arithmetic mean of the psychoacoustic annoyance (PA) was calculated for each speed limit together with the 95% CI. The arithmetic mean value from location 1 at 15 km/h is seen in table 5.13. The PA-values are slightly lower for EVs but with larger CIs than for ICEVs.

Table 5.13: Arithmetic mean of PA calculated with equation 2.13. Psychoacoustic parameters measured at location 1 with speed limit of 15 km/h.

Vehicle type	Arithmetic mean value PA	± 95 CI
EV Mic1	23.2	3.9
ICEV Mic1	25.5	2.1
EV Mic2	19.0	3.0
ICEV Mic2	20.8	1.6

In table 5.14 the PA from location 2 at 30 km/h are presented. Microphone 1 closest to the source shows insignificant small deviations between EVs and ICEVs. In contrast the results from microphone 2 indicates that the mean value of PA is considerably lower from EVs. Important is to keep in mind that the CI for both microphones shows large spread of the calculated PA from each passage.

Table 5.14: Arithmetic mean of PA calculated with equation 2.13. Psychoacoustic parameters measured at location 2 with speed limit of 30 km/h.

Vehicle type	Direction	Arithmetic mean value PA	± 95% CI
EV Mic1	Northeast	33.0	4.0
ICEV Mic1	Northeast	33.1	4.8
EV Mic1	Southwest	25.2	4.2
ICEV Mic1	Southwest	30.3	6.6
EV Mic2	Northeast	27.6	3.5
ICEV Mic2	Northeast	27.8	4.2
EV Mic2	Southwest	21.7	3.9
ICEV Mic2	Southwest	26.8	6.1

The arithmetic mean of PA is 2.2 to 3.6 lower for EVs at location 3 at 40 km/h than ICEVs seen in table 5.15.

Table 5.15: Arithmetic mean of PA calculated with equation 2.13. Psychoacoustic parameters measured at location 3 with speed limit of 40 km/h.

Vehicle type	Direction	Arithmetic mean value PA	± 95% CI
EV Mic1	East	16.1	2.6
ICEV Mic1	East	19.7	2.6
EV Mic1	West	15.4	2.1
ICEV Mic1	West	19.0	1.9
EV Mic2	East	13.1	2.1
ICEV Mic2	East	16.3	2.1
EV Mic2	West	13.2	1.8
ICEV Mic2	West	15.4	1.4

The trend at location 4 at 50 km/h is that the mean value of PA is almost identical in the northwestern direction. In the southeastern direction the deviation of the mean value is up to 5.1. Noteworthy is although that the CI are relative large for all calculated values.

Table 5.16: Arithmetic mean of PA calculated with equation 2.13. Psychoacoustic parameters measured at location 4 with speed limit of 50 km/h.

Vehicle type	Direction	Arithmetic mean value PA	± 95% CI
EV Mic1	Southeast	15.9	3.9
ICEV Mic1	Southeast	21.0	3.5
EV Mic1	Northwest	26.4	3.6
ICEV Mic1	Northwest	25.9	2.8
EV Mic2	Southeast	14.1	3.9
ICEV Mic2	Southeast	18.7	3.1
EV Mic2	Northwest	22.1	3.0
ICEV Mic2	Northwest	22.2	2.4

In table 5.17 the arithmetic mean value of PA for location 5 at 60 km/h is presented. It can be seen that for all comparison that the EV have lower values than ICEV. Once again the CI are large which indicates that the spread of the individual values deviates.

Table 5.17: Arithmetic mean of PA calculated with equation 2.13. Psychoacoustic parameters measured at location 5 with speed limit of 60 km/h.

Vehicle type	Direction	Arithmetic mean value PA	± 95% CI
EV Mic1	South	28.2	2.2
ICEV Mic1	South	34.8	4.4
EV Mic1	North	27.3	3.7
ICEV Mic1	North	30.3	3.6
EV Mic2	South	25.2	2.0
ICEV Mic2	South	31.6	4.1
EV Mic2	North	25.0	3.7
ICEV Mic2	North	28.1	3.5

5.9 Listening test

The results from the listening test are presented below where the average of answers from the 20 participants are shown together with the standard deviation and the CI. The participants were asked to rate each sound on a scale from 0 to 10 where 0 equaled "not annoying at all" and 10 equaled "Extremely annoying". Note that the difference in distance between the source and receiver are different for each speed which leads to that no direct comparison between each speed limit can be compared. In table 5.18 the results from location 1 with the speed limit of 15 km/h are presented. The difference within each vehicle type deviates more than between both categories where both sounds from each category have received similar score.

Table 5.18: Results from listening test of vehicles driving at speed limit of 15 km/h.

Vehicle type	Average	Standard deviation	± 95% CI
EV Sound 1	5.95	1.86	0.81
EV Sound 2	6.70	1.62	0.71
ICEV Sound 1	5.85	1.82	0.80
ICEV Sound 2	6.65	1.98	0.87

In table 5.19 the results from location 2 with the speed limit of 30 km/h are presented. The average rating of both the EVs stimulus are close to each other. In opposite ICEVs received both the lowest and highest average obstructing the view to see any clear trends.

Table 5.19: Results from listening test of vehicles driving at speed limit of 30 km/h.

Vehicle type	Average	Standard deviation	± 95% CI
EV Sound 1	5.15	1.68	0.74
EV Sound 2	4.60	1.53	0.67
ICEV Sound 1	6.45	1.56	0.69
ICEV Sound 2	3.75	1.30	0.57

The same trend as for 15 km/h can be seen in table 5.20 where both vehicles type have received closely related averages.

Table 5.20: Results from listening test of vehicles driving at speed limit of 40 km/h.

Vehicle type	Average	Standard deviation	± 95% CI
EV Sound 1	3.90	1.48	0.65
EV Sound 2	4.45	1.50	0.66
ICEV Sound 1	3.85	1.53	0.67
ICEV Sound 2	4.30	1.49	0.65

The results from the chosen stimulus at 50 km/h are seen in table 5.21. The average of the two stimulus of EVs was rated closely around 7.0. The same phenomena as at 30 km/h occurred resulting in that the ICEVs had both the lowest and highest rated annoyance but with an average approximately the same as the EVs.

Table 5.21: Results from listening test of vehicles driving at speed limit of 50 km/h.

Vehicle type	Average	Standard deviation	± 95% CI
EV Sound 1	6.90	1.51	0.66
EV Sound 2	7.00	1.55	0.68
ICEV Sound 1	7.45	1.83	0.80
ICEV Sound 2	6.50	1.86	0.81

At last the results from the listening test of stimulus of vehicles passing at 60 km/h are presented in table 5.22. The two stimulus of EVs were rated as average 6.30 and 6.75 in comparison to the ICEVs which had an average of 7.50 and 7.65. The ICEVs were in general rated with a score of around 1 higher then the EVs at this speed limit.

Table 5.22: Results from listening test of vehicles driving at speed limit of 60 km/h.

Vehicle type	Average	Standard deviation	± 95% CI
EV Sound 1	6.75	1.76	0.77
EV Sound 2	6.30	1.65	0.72
ICEV Sound 1	7.50	1.88	0.83
ICEV Sound 2	7.65	1.77	0.78

5.10 Statistical results

The results from the statistical calculations are seen in appendix A.44 to A.47. In appendix A.44 and A.45 the SEL was compared for EVs and ICEVs respectively with the age of each vehicle, the speed limit and the vehicle's weight. Studying the speed limit it can be seen that there are only small differences between the EVs and the ICEVs. The weight of the EVs can also be seen to influence the noise level linearly when the weight of the vehicle is used with a logarithmic scale. Noteworthy is that the EVs are at most 10 years old compared to the ICEVs which have a much larger span. The relation between maximum SPL and the chosen variables are seen in appendix A.46 and A.47. The same trends are observed as for SEL.

6

Discussion

This chapter aims to discuss the results presented in the earlier chapter dependent of the three questions defined in the beginning of the report. Comparisons of the newly found results will be compared to findings found in the literature review and discussed. In addition thoughts of the method used for this report will be discussed.

6.1 Evaluation of L_{AE}, L_{Amax} and L_{AW}

When comparing the EVs with ICEVs at 15 km/h it can be seen that EVs were approximately 2 dBA lower for both L_{AE} and L_{Amax}. This is reflected in the spectra where the curves of both EVs and ICEVs are similar but ICEVs are a few decibel higher. The small difference of up to 2 dBA also falls within overlapping CI. In addition, with almost equal values of L_{WA} at 15 km/h these results were unexpected since the deviations seen in the literature were larger at lower speeds. Since the speed of each vehicle was not measured this could influence the results but this study was also made with a larger number of vehicles compared to many of the studies in the literature review. When just comparing small sets of vehicles their properties affect the final results in a greater extent compared to this work where it is supposed to reflect an average of the large vehicle fleet existing.

Studying the spectra of the vehicles it was seen in the literature review that both vehicle types began to emit approximately the same noise levels between 20 km/h and 40 km/h. Seen in the results of the third-octave bands for L_{AE} and L_{Amax} the curves for the two vehicle types seem to be following each other already from 15 km/h. This is surprising since the propulsion noise from ICEVs were expected to dominate at lower speeds affecting the noise to distinguish them from EVs. However it was seen in the literature review that from the COMPETT project, clear differences were seen in the spectra when the speed of the vehicle was only around 10 km/h. This was also seen in the study from Japan when the vehicles drove at 10 km/h but when reaching 20 km/h the noise from one of the EVs were in the same range as the ICEVs. An observation made during the measurement is that EVs today are in the same size and weight as ICEVs compared to when EVs first were introduced to the market, then being smaller and not as developed. Thus EVs today do not have the advantage of being lighter than ICEVs, which generates the noise emission from vehicles.

In the comparison with the calculated sound power level by the CNOSSOS-EU source model and the corresponding value from the measurement it was seen both for the single number value and in the spectra at each speed limit that CNOSSOS slightly overestimated the noise level. In the comparison between the vehicle types the differences were insignificant at 15 km/h to 40 km/h. At 50 km/h and 60 km/h EVs were emitting more noise even though the difference was at most 1.9 dBA. In the literature review it was seen both in the COMPETT project and in the Japanese study from 2012 that the noise between EV and ICEV deviated at low speeds when looking at the spectra. This trend was not seen in the lower speed neither when evaluating L_{AE}, L_{Amax} or L_{AW}. This could be explained by that both the vehicles types emitted closely related noise level.

6.2 How does the speed influence the noise emission

Early findings from the literature review indicated that the difference in noise emission between EVs and ICEVs is affected by the speed of the vehicle as expected since the dominating noise source of vehicles shifts from propulsion noise to tyre/road noise at a some cross-over speed. As the tyre/road noise starts to dominate the noise emission one could expect a more similar noise emission from the different vehicle types. The literature review showed that EVs were quieter at lower speeds and as the speed increases the deviation between the vehicle types decreased. This trend could be seen for all studies except from the master thesis presented at the Technical University of Denmark in 2012. However the deviation between the vehicle types dependent of the speed deviated greatly within the literature review. The study in Japan 2010 and its follow up study 2012 indicated that the noise emission from the vehicle types became equal around 20 km/h compared to the CityHush project which presented deviation of 7 to 8 dBA for the maximum SPL at 50 km/h. The spread in the difference seen in the literature review and how the speed influences the noise emission could be explained by that many of the studies were based on a small set of vehicles. This leads to that the properties of the vehicles can deviate between each study, thus making it hard to directly compare the vehicle types individually.

Looking at the results of the single number values of the SEL and maximum SPL in the present study a slight trend can be seen that EVs emits less noise over all the speed limits. However the differences are at most 2.5 dBA and are not judged as a significant difference. Taking into account that the 95% CIs overlap makes it uncertain to determine the deviation between the vehicle types. The differences are also in the same range for all the speed limits which makes it hard to distinguish the cross-over speed where the dominating noise source is expected to go from being the propulsion noise to the tyre/road noise and which should show a larger deviation between the vehicle types at lower speed. From the estimated sound power level from the measured data for each speed it can also be seen that the noise increases as the speed does but the deviation between EVs and ICEVs is small. In addition the listening test did not show any results that indicate that EVs were rated to have a lower perceived annoyance than ICEVs at lower speed. The deviation between the noise from EVs and ICEVs depending of the vehicle speed is therefore not seen as obvious as in the literature review where the deviations were seen at lower speeds and decreased as the speed increased. As stated before this could be an effect of that the studies were based on a smaller set of vehicles which eliminates the possibility to estimate the average over the vehicle fleet. The noise emission from road traffic also involves a complex contribution of many noise sources which is influenced greatly if the properties deviate within a small set of vehicles.

6.3 Psychoacoustic annoyance and listening test ratings

The PA was calculated together with a listening test to asses whether there are other parameters which influence how the noise is perceived and could show deviations between the different vehicle types. From the PA EVs could be seen to have lower annoyance values than ICEVs at all speed. At the same time at 30 km/h and 50 km/h, both vehicle types received almost identical perceived values from the listening test in certain directions which obstructs this trend. Furthermore the CI calculated for the values of PA indicate that the differences are not significant.

The results from the listening test were interesting since the first thought was that the participants would rate the annoyance from ICEVs higher then EVs at least at the lower speeds. This thought was based upon the previous knowledge from the literature review that the EVs had shown lower measured values at the lower speeds. However the results from the listening test did not display this and the differences between both vehicle types were larger within each category then between them. The CI from the results were small which indicates that the ratings can be considered credible. The vague difference between both vehicle types is in line with what Dudenhoffer and Hause discovered in their survey were 240 participants rated noise from a BEs and ICEVs driving at 30 km/h which resulted in a small difference in the perceived noise level.

6.4 Method

During the work of this report two different methods have been used. To perform measurements is an important key to be able to evaluate the noise. The set up of the measurements were based on the ISO 362-1:2022 standard. The main difference between the standard and the measurements were that the distance between the noise source and the receiver deviated between each location compared to the distance of 7.5 meter given in the standard. This was caused by that the different surroundings at each location demanded different placements of the equipment. To be able to compare the results from each location to each other also the sound power level was estimated which is a metric independent of the distance to the source. However to be able to compare the results from the L_{AE} and the maximum SPL between the different speed limits it would have been favourable to have the same distance between the noise source and receiver. Another factor that was weighted in was to collect as much data as possible during the measurements to get better statistical data. This was achieved by collecting data from both traffic lanes which was not possible without ending up with the distance deviation and could only have been avoided if the measurement was carried out by two persons at each side of the road or skip half of the passages. An assumption was that all the vehicles drove at the speed of the given speed limit at each location which most likely not is the case and influences the noise emission from the vehicle. This leads to that results from each location have outliers seen in figure 5.19 which affect the final result from each location. Since the aim of the work was to evaluate how the noise from a road deviate on a daily basis between EVs and ICEVs rather then in laboratory environments these outliers represent actually cases that should not be disregarded. If it has happened once the probability that it can happen again is present.

The listening test was constructed of 2 stimuli from each vehicle type and speed limit resulting in 20 stimuli. In the process of choosing which stimuli to use each individual L_{AE} curve was compared to the average calculated curve to find the most representing stimuli. Since the recordings were made at different distances to the source it prevented comparison of the rated value directly between different speed limits since the loudness of the recordings affects the perceived annoyance. To improve the listening test measurements could be made as discussed before with equal distances to the source so comparisons can be made between each speed limit. It would also have been interesting to ask the participants whether it was possible to detect whether is was an EV or an ICEV that was rated.

7

Conclusion

Since electrical vehicles were introduced to the market the common opinion has been that EVs are quieter than internal combustion engine vehicles at lower speed since the propulsion noise deviates between the vehicle types. The work of this report aimed to investigate whether this assumption is correct by measuring passenger cars between 15 km/h and to 60 km/h with an including listening test. The results from the measurements indicate that there is a possibility that EVs emits less noise than ICEVs but the measured deviations are not larger than 3 dB in regards of L_{AE} or L_{Amax}. In combination with the confidence interval overlapping and for some cases the EVs and ICEVs had similar noise levels it cannot be verified that EVs are quieter. The estimated sound power level indicates that the difference between both vehicle types is insignificantly small and that the calculated value for light vehicles in CNOSSOS is slightly overestimating up to 50 km/h regardless of it being an EV or ICEV.

The results from the listening test indicate that the subjective perception of how annoying the noise from EVs and ICEVs was hard to distinguish. It could be seen in the results that the participants did not rate EVs less annoying than ICEVs and there were larger differences within the ratings of each vehicle type than between them. The results from calculations of psychoacoustic annoyance showed that EVs had lower values than ICEVs but the differences did not show a clear trend and the relatively large CI obstructed clear conclusions to be made. It can therefor be stated that more research is needed within this area to further develop the knowledge and investigate whether EVs will contribute to the noise abatement of road traffic noise in the future.

7.1 Future work

As the results from the project were unexpected for the lower speed limits, where the differences between the vehicle types were small, it is important to continue the research within this area. As an extension to this project a suggestion is to repeat the measurements at another city. The results could then be verified or new findings could be seen. It is also recommended to not delimit the study to only lower speed limits but rather try and evaluate all the speed limits to be able to conclude that the noise emission for the different vehicle types are equal at the higher speed limits as it is expected today. In the future work it is important to be able to measure the speed of the vehicle during the measurement, which would enable better correlation between the vehicle's speed and its noise emission.

Bibliography

[1] World Health Organization. *Environmental noise guidelines for the European Region.* WHO Regional Office for Europe, 2018.

[2] María Carmen Pardo-Ferreira et al. “New risk situations related to low noise from electric vehicles: Perception of workers as pedestrians and other vehicle drivers”. In: *International Journal of Environmental Research and Public Health* 17 (18 2020). ISSN: 16604601. DOI: `10.3390/ijerph17186701`.

[3] A Tsakalidis and C Thiel. *Electric vehicles in Europe from 2010 to 2017: is full-scale commercialisation beginning?* Publications Office of the European Union, 2018.

[4] Emanuel Hammer et al. “Traffic noise emission modelling at lower speeds”. In: 2016.

[5] Rasmus Stahlfest Holck Skov and Lykke Møller Iversen. *Noise from electric vehicles - Measurements.* 2013.

[6] Sigmund Olafsen and Atle Stensland. “Tram noise monitoring”. In: 2018.

[7] David Norenius. “Potential Noise Reduction with Electric Vehicles”. Division of Applied Acoustics, 2020.

[8] Malene monslaup. “An investigation into the psychoacoustic characteristics of train noise in Oslo, and their effect on annoyance”. Faculty of Information Technology and Electrical Engineering, 2019.

[9] M. Paviotti F. Anfosso-Lédée S. Kephalopoulos. *Common Noise Assessment Methods in Europe (CNOSSOS-EU).* 2012.

[10] F. Alton; Pohlmann Ken C. Everest. *Master Handbook Of Acoustics 5th. Edition.* 2009.

[11] M Kleiner. *Acoustics and Audio Technology.* 2012.

[12] Jens Forssén et al. “A model study of low-frequency noise exposure indoors due to road traffic”. In: *Building Acoustics* 30 (1 Mar. 2023), pp. 3–24. ISSN: 1351-010X. DOI: `10.1177/1351010X221143571`.

[13] William J Murphy. *Plaques of Lambda Phages on E. coli XL1-Blue MRF.* "2016". URL: `https://commons.wikimedia.org/wiki/File:ABC_Weighting.png`.

[14] Ulf Sandberg. *Guidance manual for the implementation of low-noise road surfaces.* 2006. URL: `https://www.diva-portal.org/smash/get/diva2:1716827/FULLTEXT01.pdf`.

[15] W Keulen and M Duskov. *Inventory Study of Basic Knowledge on Tire/Road Noise (Report number: DWW-2005-022).* 2005.

[16] Malcolm J. Crocker. *Handbook of Noise and Vibration Control.* 2008. DOI: `10.1002/9780470209707`.

[17] Ulf Jerzy A. Sandberg and Ejsmont. *Tyre/Road Noise Reference Book.* 2002.

[18] R. E. Hayden. “Roadside Noise from the Interaction of a Rolling Tire with the Road Surface”. In: *The Journal of the Acoustical Society of America* 50 (1A 1971). ISSN: 0001-4966. DOI: `10.1121/1.1977497`.

[19] G. Unnikrishnan et al. “A model to predict role of different tread parameters on tire noise”. In: 2015.

[20] Alice Hoffman. “PERCEPTION OF ROLLING NOISE”. Division of Applied Acoustics Chalmers University of Technology, 2015.

[21] Hugo Fastl and Eberhard Zwicker. *Psychoacoustics: Facts and models*. 2007. DOI: `10.1007/978-3-540-68888-4`.

[22] Brian C J Moore. *An Introduction to the Psychology of Hearing 6th Edition*. Vol. 3. 2003.

[23] J Lelong. “Passenger cars, power unit and tyre-road noise, driving behaviour: What are the stakes?” In: *Inter-Noise 2001 - Abstracts From International Congress and Exhibition on* (2001). ISSN: 0105-175X.

[24] Kazumoto’ ’Morita et al. “REVIEWS ON COUNTERMEASURE TO SAFETY RISK ASSOCIATED WITH QUIETNESS OF HYBRID OR ELECTRIC VEHICLES IN JAPAN”. In.

[25] Filip Stenlund. *Noise criteria for vehicles to enter Q-Zones*. 2011. URL: `http://www.cityhush.eu/downloads/Update_Cityhush201112/D030202_ACL_M18.pdf`.

[26] Ichiro Sakamoto et al. “Report on basic research for standardization of measures for quiet vehicles in Japan (Intermit report)”. In: vol. 6. 2012.

[27] Gijsjan Van Blokland. “Stimulation of low noise road vehicles in the Netherlands”. In: vol. 1. 2011.

[28] Kenneth Kaliski, Isaac Old, and Les Blomberg. “Sound emissions from a plug-in electric vehicle”. In: vol. 6. 2012.

[29] Chen Cai. “Noise emission from electric cars”. Acoustic Technology, 2012.

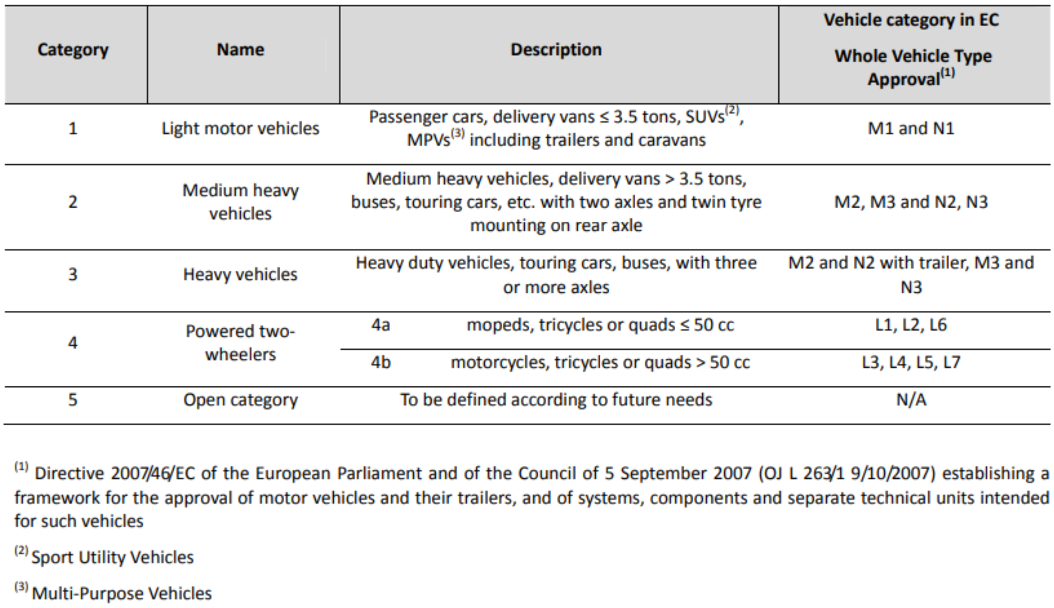
[30] Kathrin Dudenhöffer and Leonie Hause. “Sound Perception of Electric Vehicles”. In: *ATZ worldwide eMagazine* 114 (3 Mar. 2012), pp. 46–50. DOI: `10.1365/s38311-012-0158-0`.

[31] International Organization for Standardization. *Acoustics — Engineering method for measurement of noise emitted by accelerating road vehicles — Part 1: M and N categories*. 2022. URL: `https://www.iso.org/standard/80872.html`.

A

Appendix A

A.1 CNOSSOS category



Category	Name	Description		Vehicle category in EC Whole Vehicle Type Approval[1]
1	Light motor vehicles	Passenger cars, delivery vans ≤ 3.5 tons, SUVs[2], MPVs[3] including trailers and caravans		M1 and N1
2	Medium heavy vehicles	Medium heavy vehicles, delivery vans > 3.5 tons, buses, touring cars, etc. with two axles and twin tyre mounting on rear axle		M2, M3 and N2, N3
3	Heavy vehicles	Heavy duty vehicles, touring cars, buses, with three or more axles		M2 and N2 with trailer, M3 and N3
4	Powered two-wheelers	4a	mopeds, tricycles or quads ≤ 50 cc	L1, L2, L6
		4b	motorcycles, tricycles or quads > 50 cc	L3, L4, L5, L7
5	Open category	To be defined according to future needs		N/A

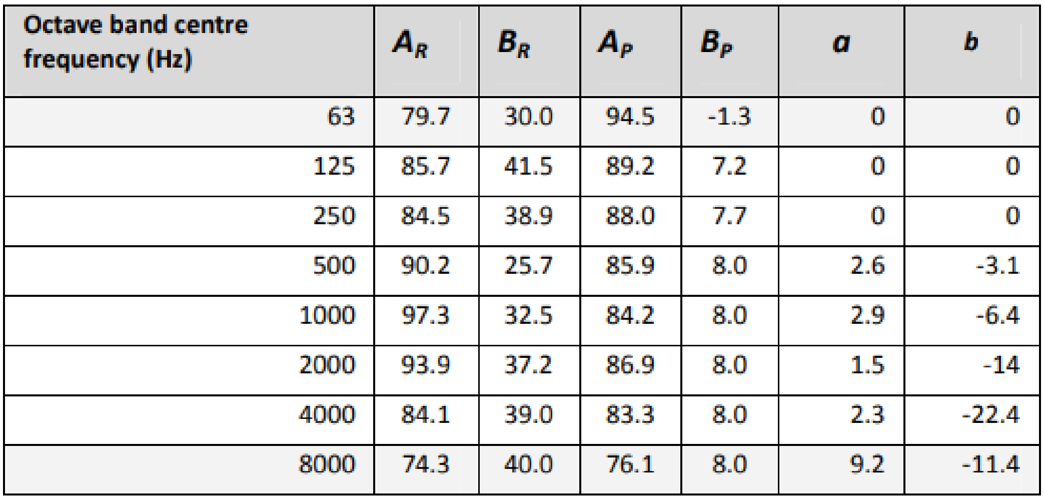
[1] Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 (OJ L 263/1 9/10/2007) establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles

[2] Sport Utility Vehicles

[3] Multi-Purpose Vehicles

Figure A.1: Definition of the different vehicle categories within the CNOSSOS-EU method [9].

A.2 Coefficients for category 1 CNOSSOS



Octave band centre frequency (Hz)	A_R	B_R	A_P	B_P	a	b
63	79.7	30.0	94.5	-1.3	0	0
125	85.7	41.5	89.2	7.2	0	0
250	84.5	38.9	88.0	7.7	0	0
500	90.2	25.7	85.9	8.0	2.6	-3.1
1000	97.3	32.5	84.2	8.0	2.9	-6.4
2000	93.9	37.2	86.9	8.0	1.5	-14
4000	84.1	39.0	83.3	8.0	2.3	-22.4
8000	74.3	40.0	76.1	8.0	9.2	-11.4

Figure A.2: Coefficients for category 1 in CNOSSOS-EU method[9].

A.3 Background noise at 15 km/h

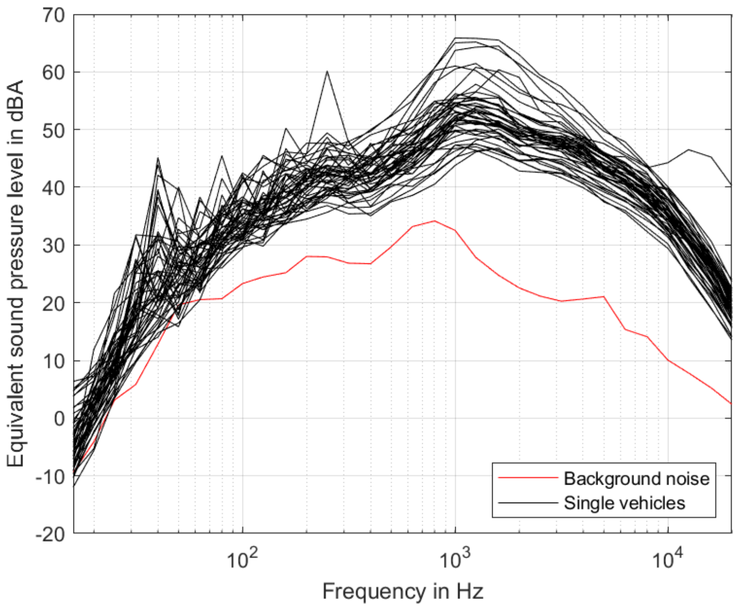


Figure A.3: Comparison of background noise with measurements of all the vehicles at 15 km/h.

A.4 Background noise at 30 km/h

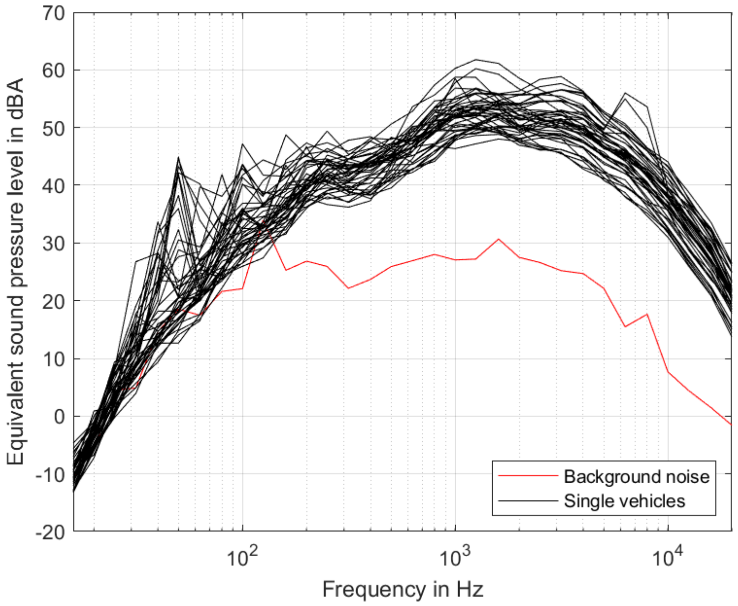


Figure A.4: Comparison of background noise with measurements of all the vehicles at 30 km/h.

A.5 Background noise at 40 km/h

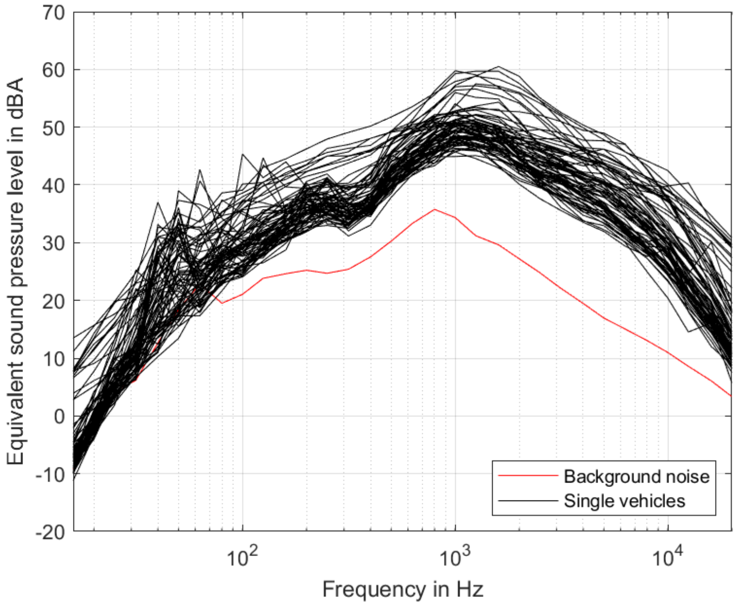


Figure A.5: Comparison of background noise with measurements of all the vehicles at 40 km/h.

A.6 Background noise at 50 km/h

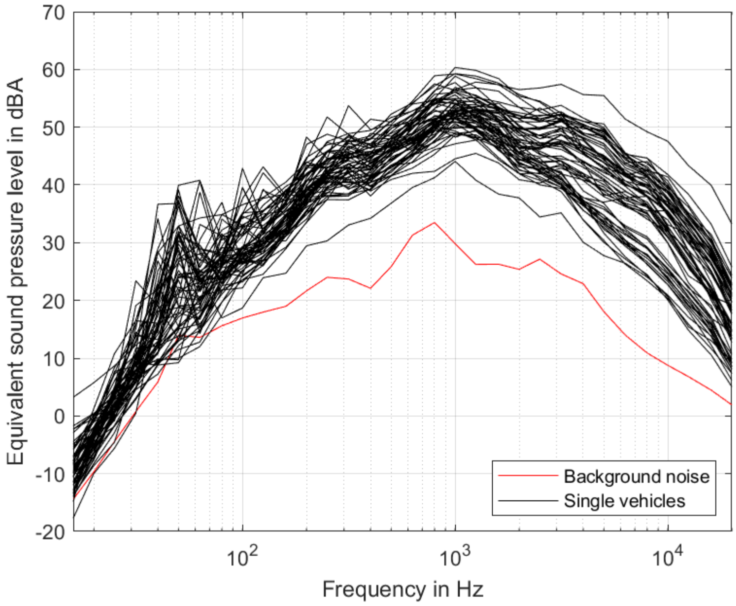


Figure A.6: Comparison of background noise with measurements of all the vehicles at 50 km/h.

A.7 Background noise at 60 km/h

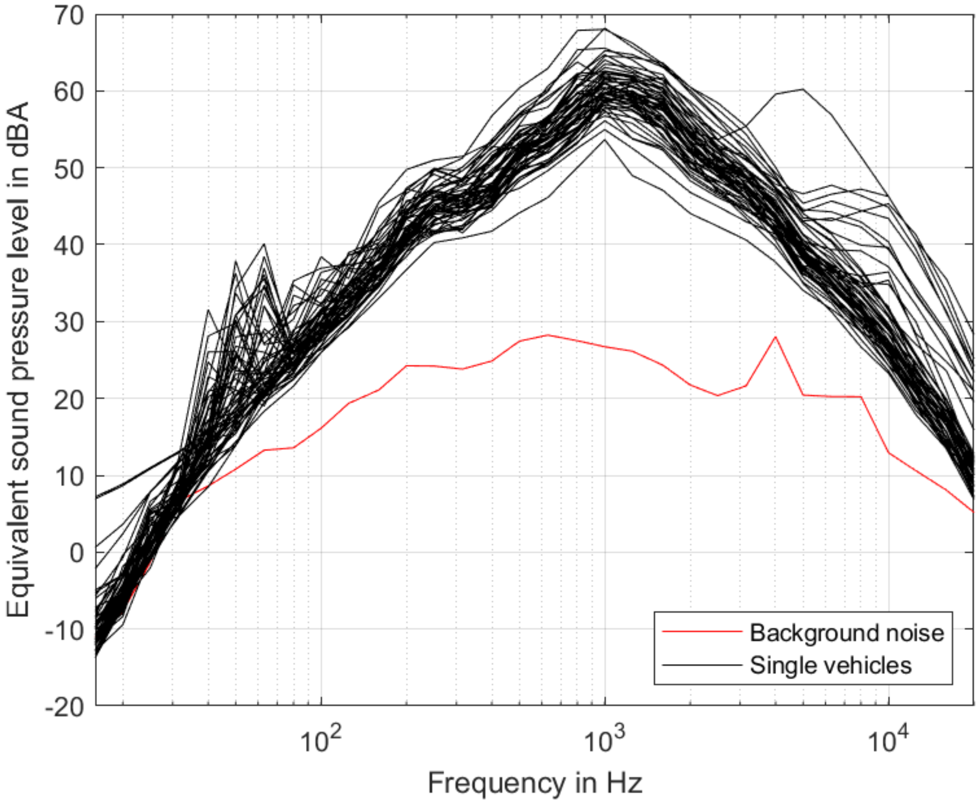


Figure A.7: Comparison of background noise with measurements of all the vehicles at 60 km/h.

A.8 Sound exposure level 15km/h Mic1

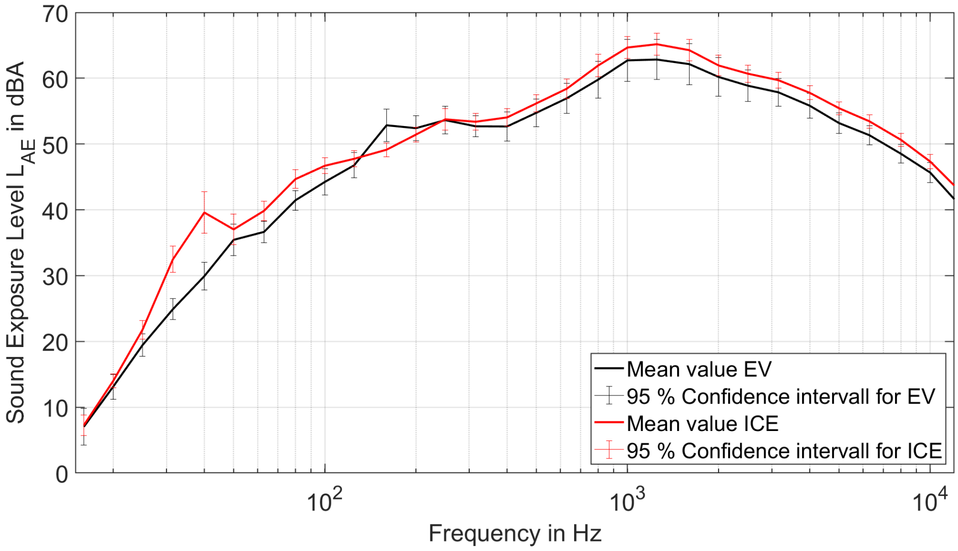


Figure A.8: L_{AE} compared between EVs and ICEVs and the 95% CI for 15 km/h and microphone 1.

A.9 Sound exposure level 15km/h Mic2

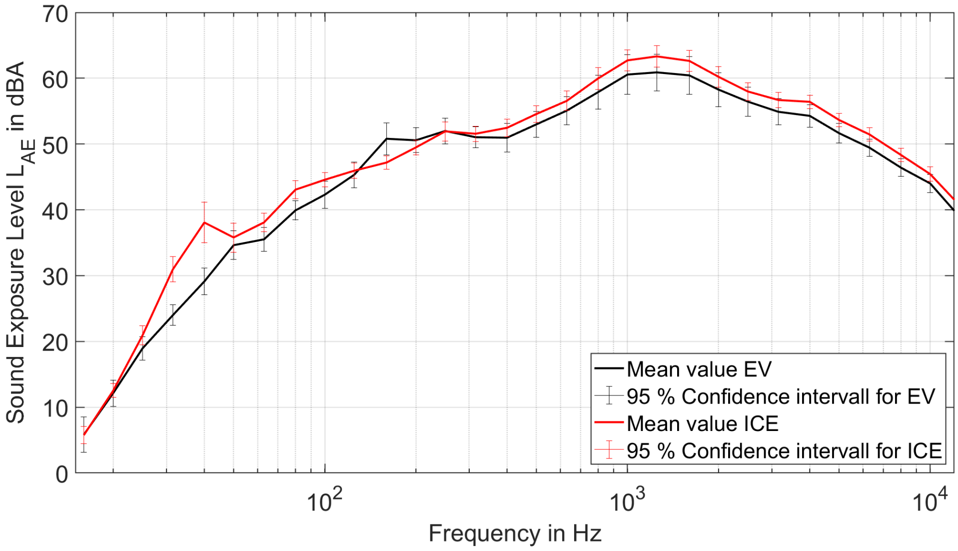


Figure A.9: L_{AE} compared between EVs and ICEVs and the 95% CI for 15 km/h and microphone 2.

A.10 Maximum sound pressure level 15km/h Mic1

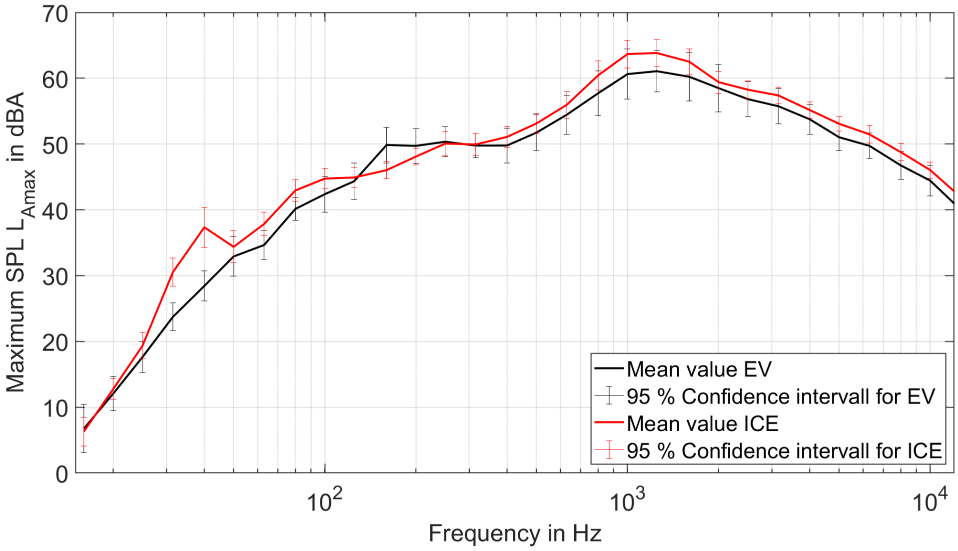


Figure A.10: L_{Amax} compared between EVs and ICEVs and the 95% CI for 15 km/h and microphone 1.

A.11 Maximum sound pressure level 15km/h Mic2

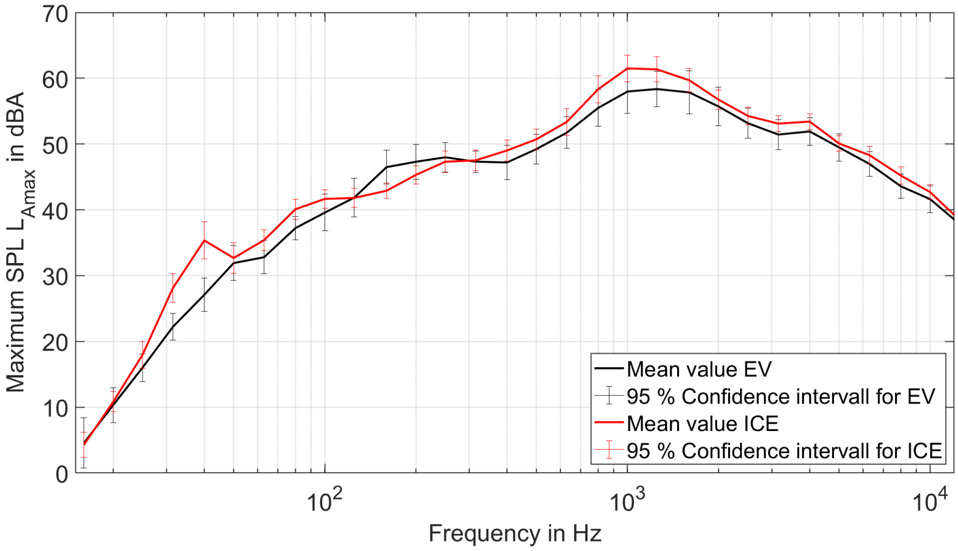


Figure A.11: L_{Amax} compared between EVs and ICEVs and the 95% CI for 15 km/h and microphone 2.

A.12 Sound exposure level 30km/h Mic1 North-East

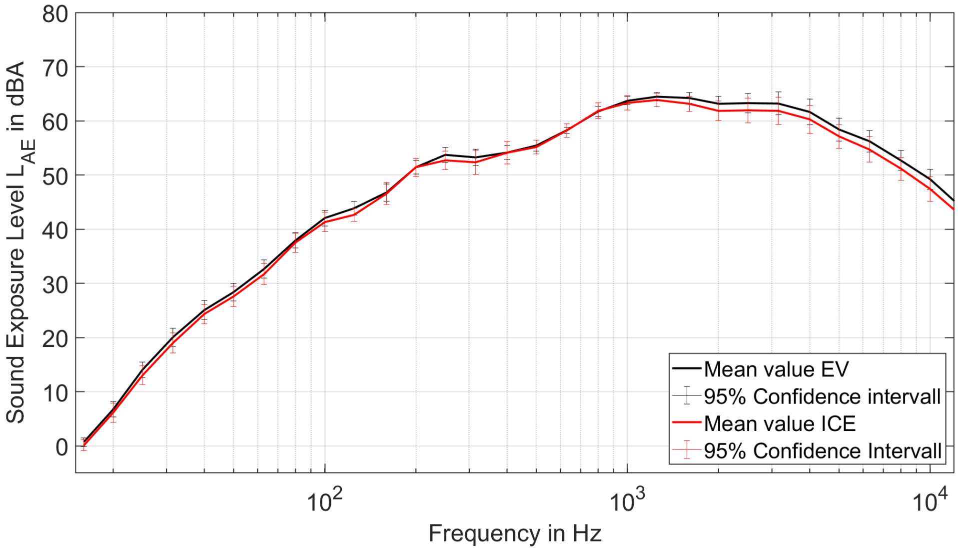


Figure A.12: L_{AE} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 1 at north-east.

A.13 Sound exposure level 30km/h Mic2 North-East

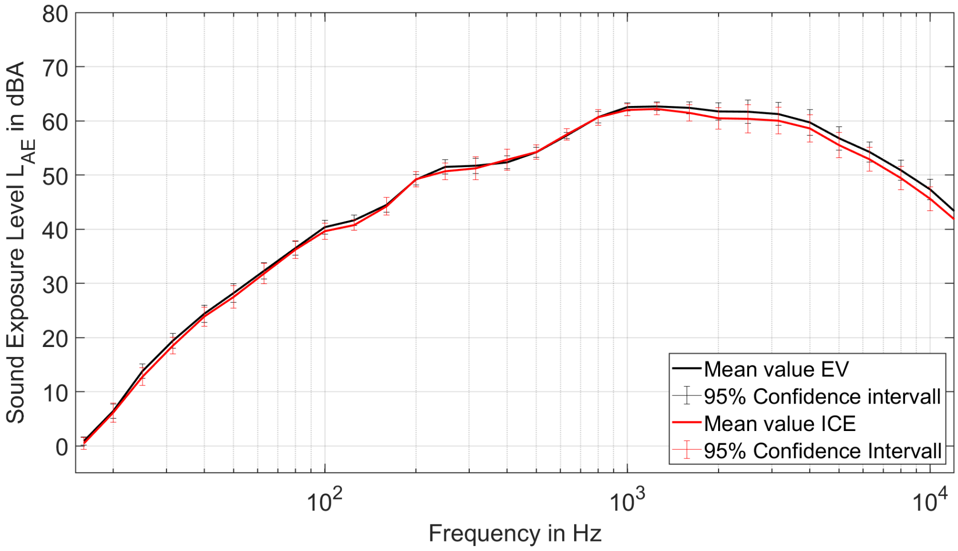


Figure A.13: L_{AE} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 2 at north-east.

A.14 Sound exposure level 30km/h Mic1 South-West

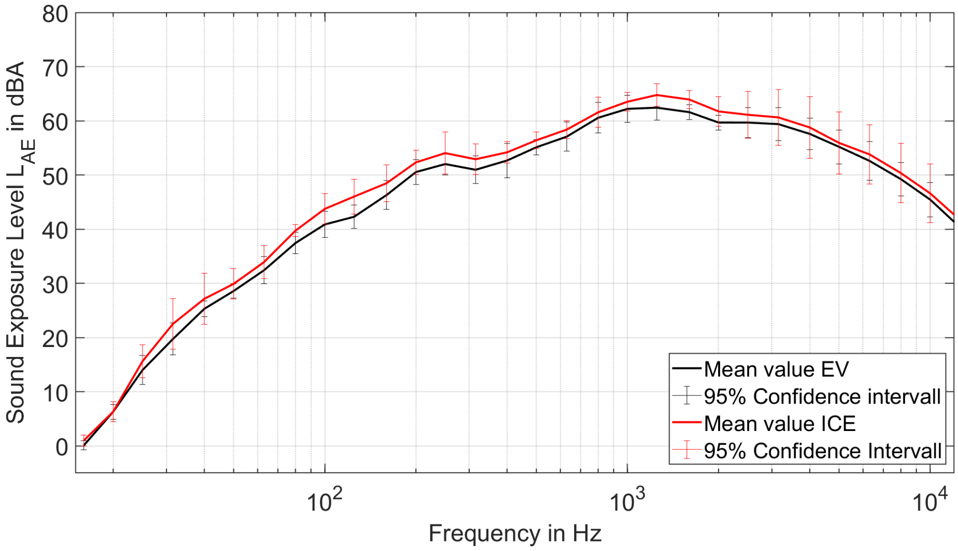


Figure A.14: L_{AE} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 1 at south-west.

A.15 Sound exposure level 30km/h Mic2 South-West

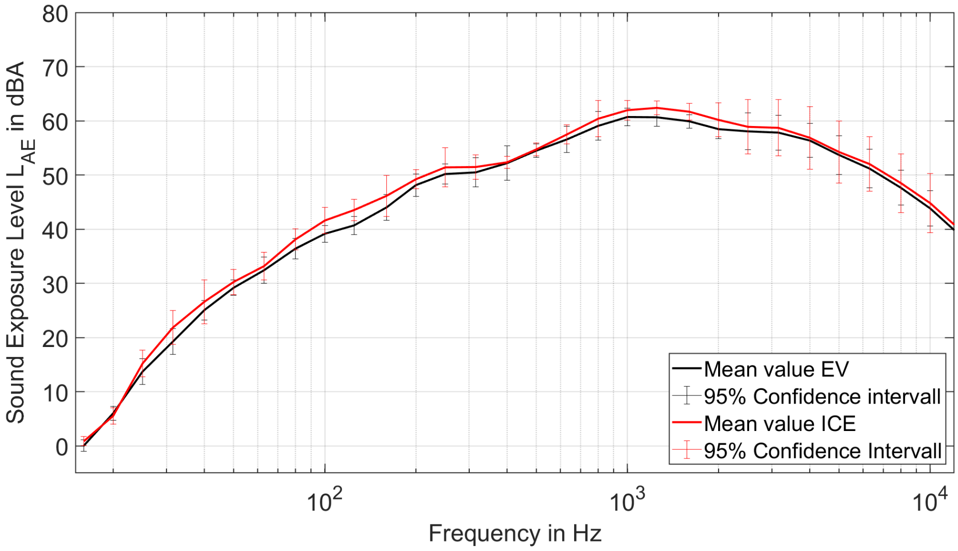


Figure A.15: L_{AE} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 2 at south-west.

A.16 Maximum sound pressure level 30km/h Mic1 Northeast

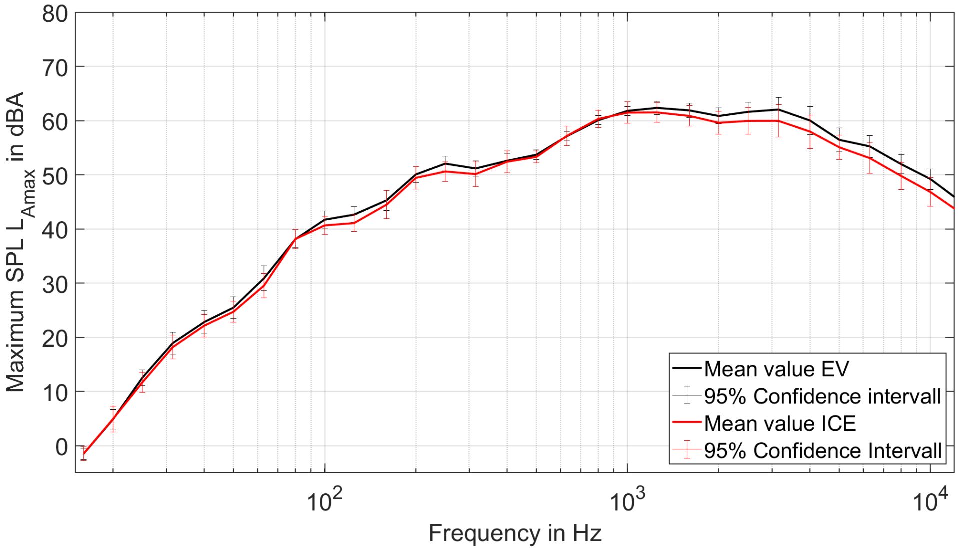


Figure A.16: L_{Amax} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 1 at northeast.

A.17 Maximum sound pressure level 30km/h Mic2 Northeast

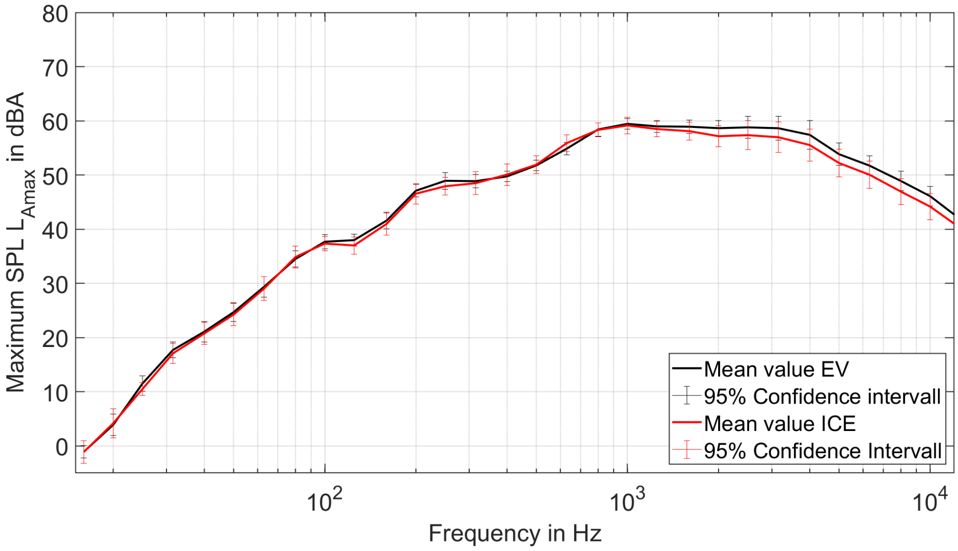


Figure A.17: L_{Amax} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 2 at northeast.

A.18 Maximum sound pressure level 30km/h Mic1 Southwest

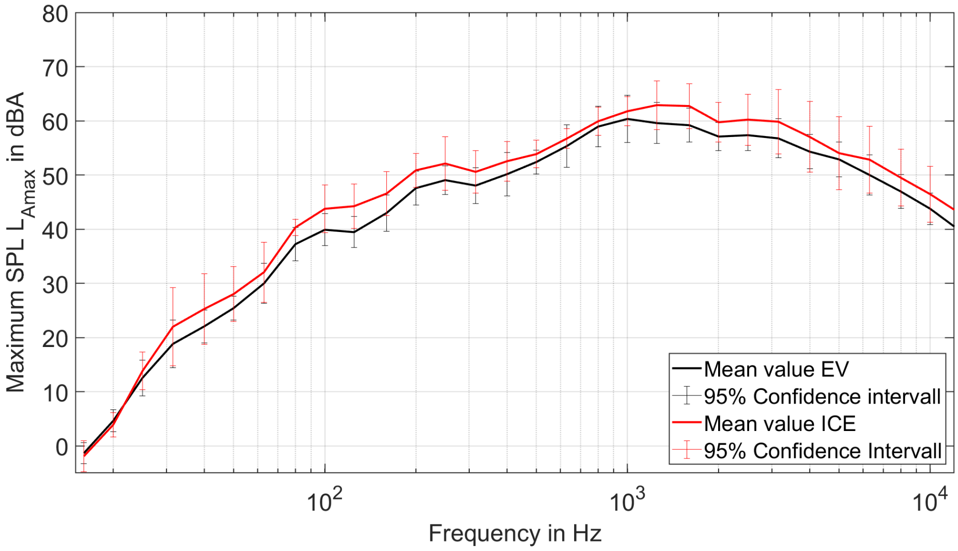


Figure A.18: L_{Amax} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 1 at southwest.

A.19 Maximum sound pressure level 30km/h Mic2 Southwest

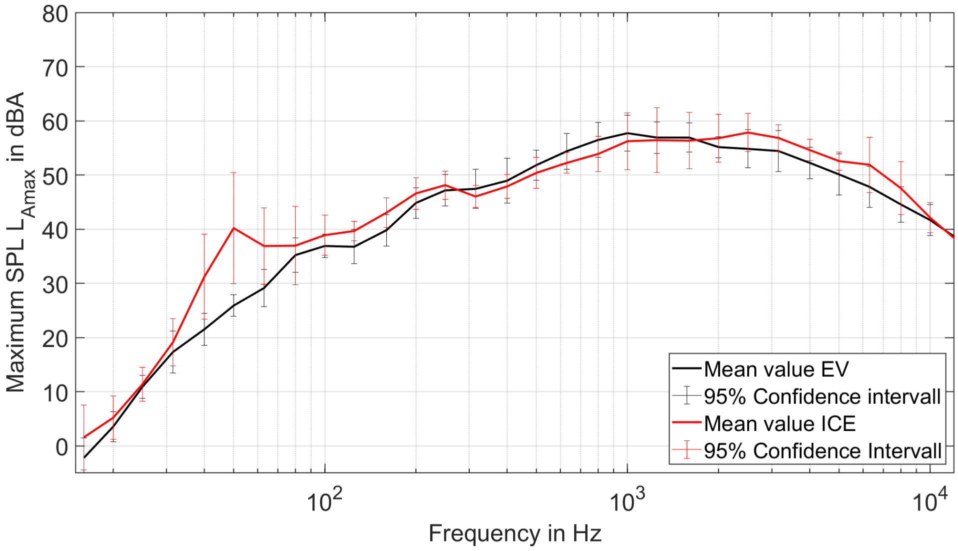


Figure A.19: L_{Amax} compared between EVs and ICEVs and the 95% CI for 30 km/h and microphone 2 at southwest.

A.20 Sound exposure level 40km/h Mic1 East

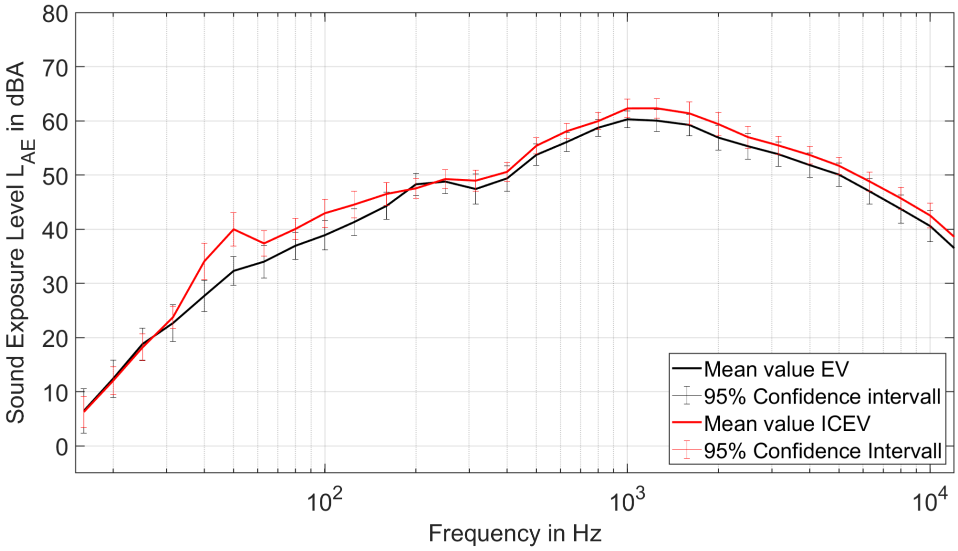


Figure A.20: L_{AE} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 1 at east.

A.21 Sound exposure level 40km/h Mic2 East

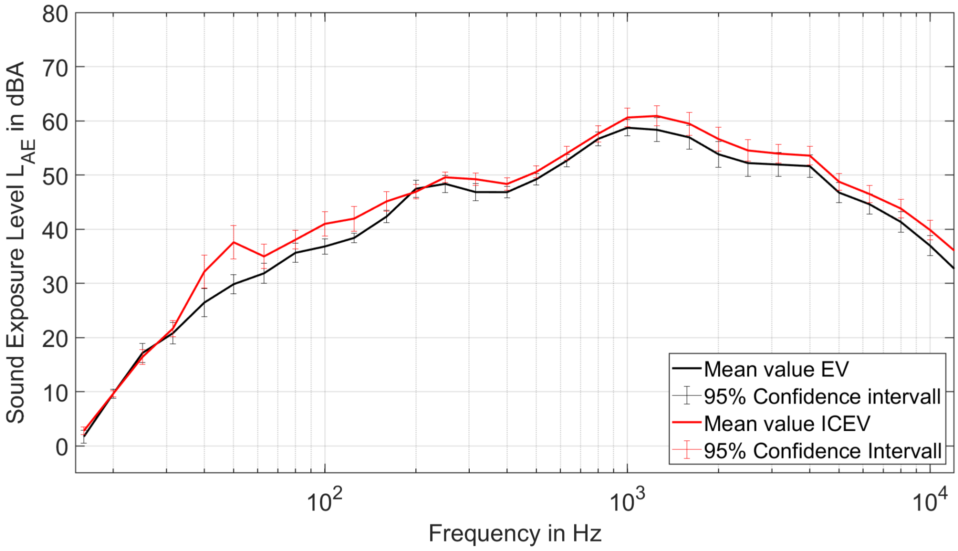


Figure A.21: L_{AE} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 2 at east.

A.22 Sound exposure level 40km/h Mic1 West

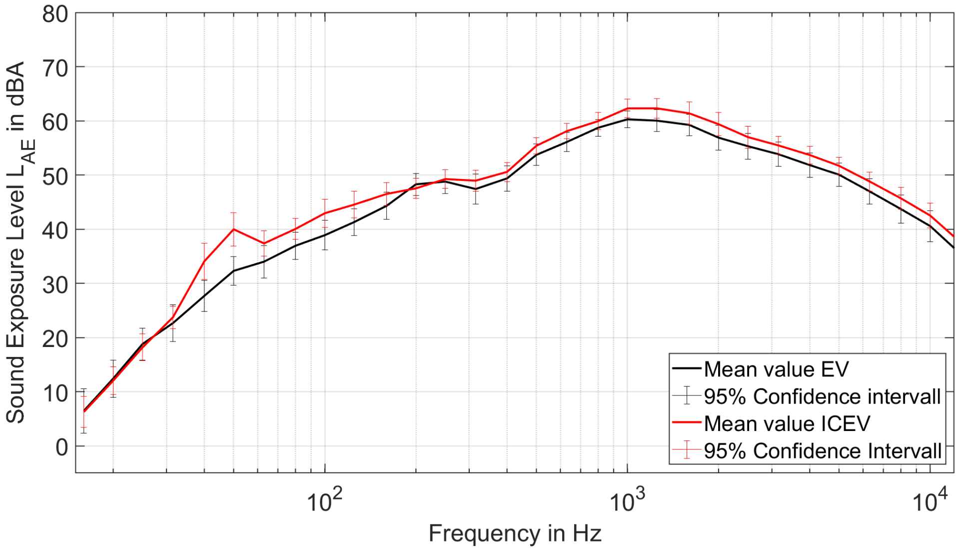


Figure A.22: L_{AE} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 1 at west.

A.23 Sound exposure level 40km/h Mic2 West

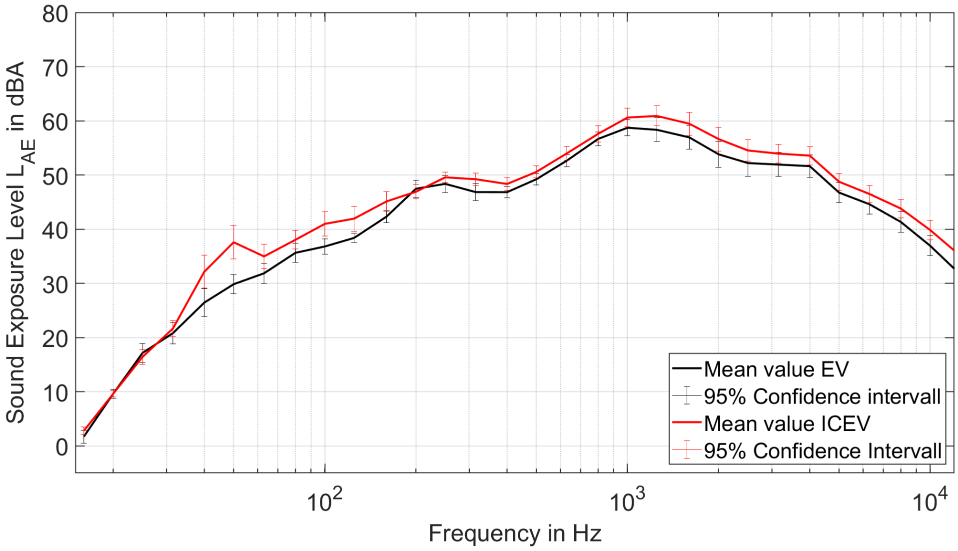


Figure A.23: L_{AE} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 2 at west.

A.24 Maximum sound pressure level 40km/h Mic1 East

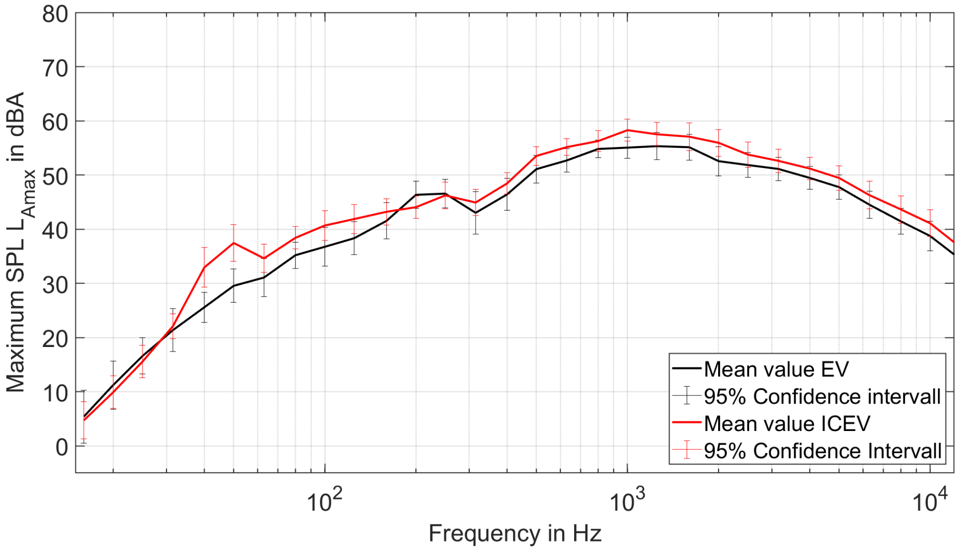


Figure A.24: L_{Amax} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 1 at east.

A.25 Maximum sound pressure level 40km/h Mic2 East

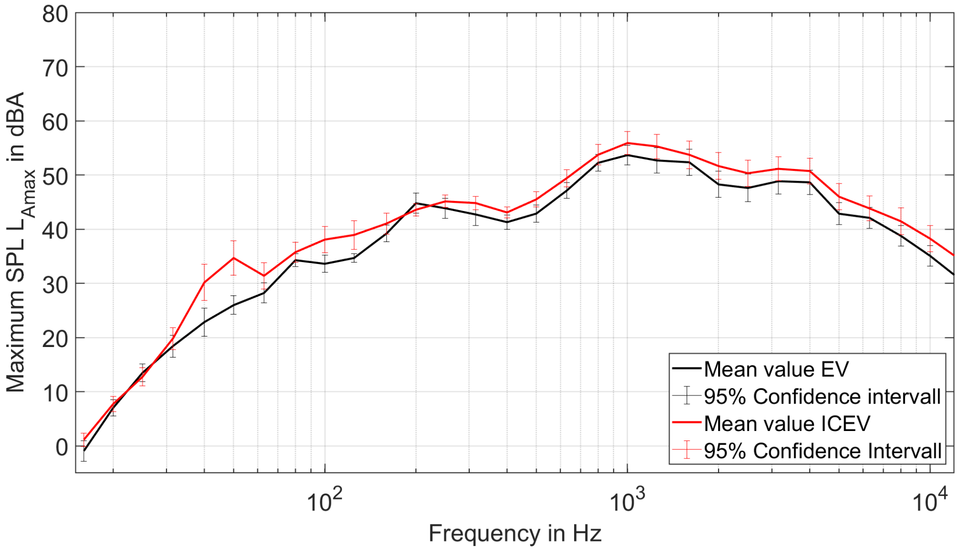


Figure A.25: L_{Amax} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 2 at east.

A.26 Maximum sound pressure level 40km/h Mic1 West

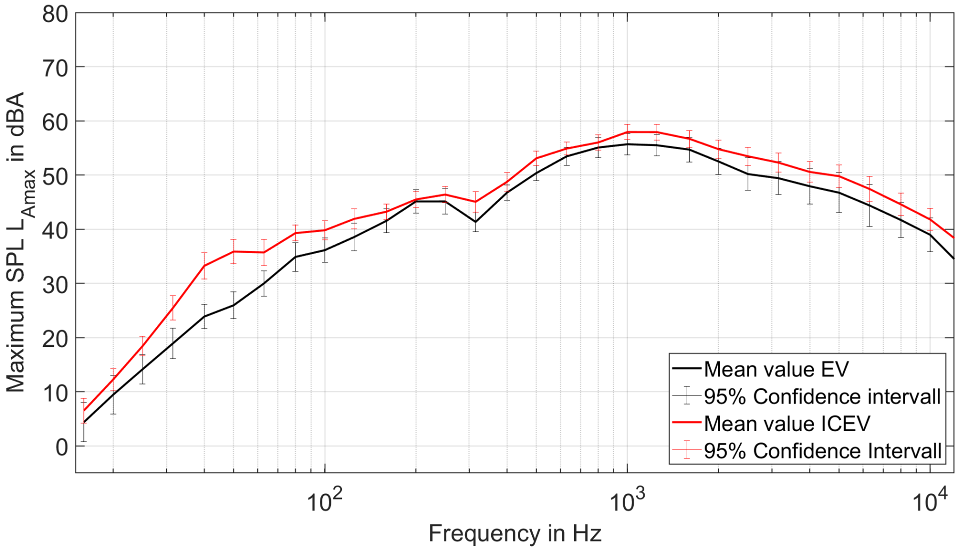


Figure A.26: L_{Amax} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 1 at west.

A.27 Maximum sound pressure level 40km/h Mic2 West

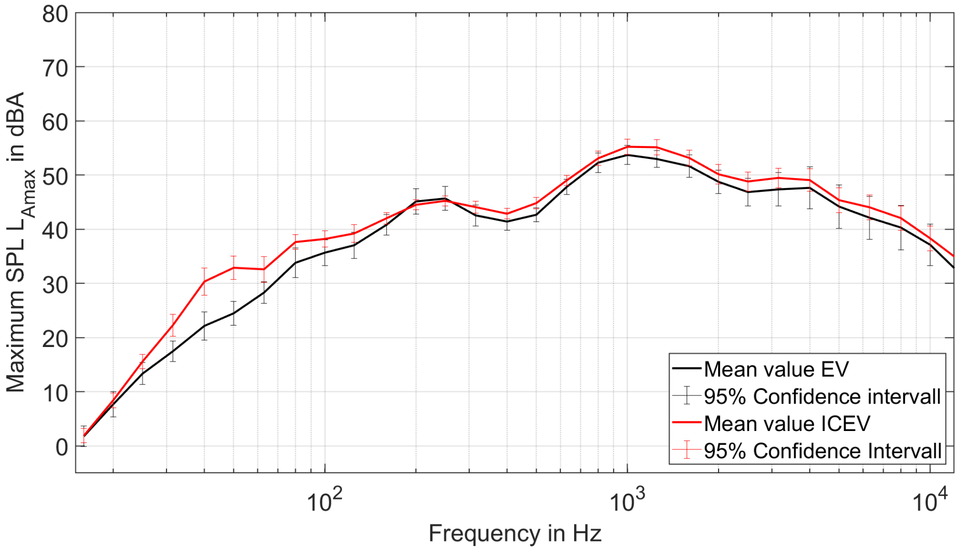


Figure A.27: L_{Amax} compared between EVs and ICEVs and the 95% CI for 40 km/h and microphone 2 at west.

A.28 Sound exposure level 50km/h Mic1 North-west

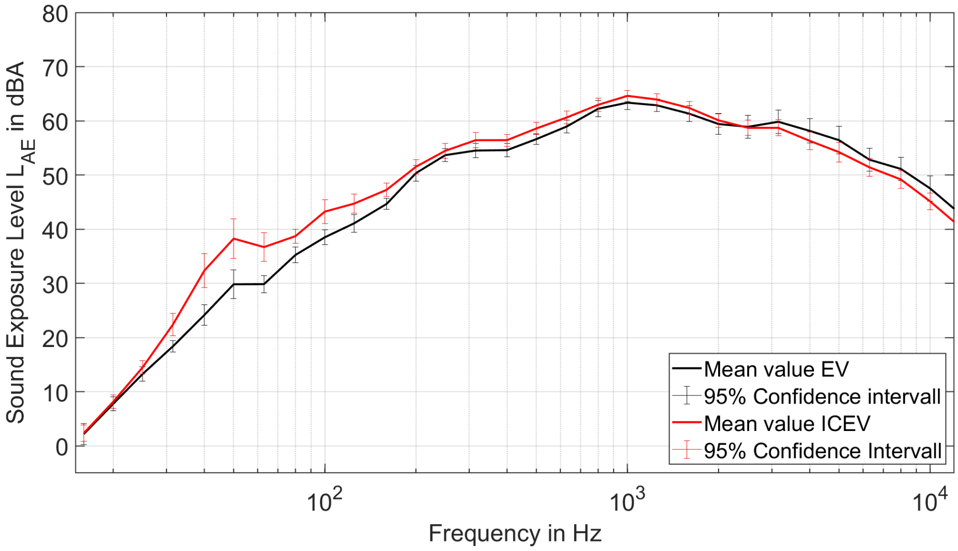


Figure A.28: L_{AE} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 1 at north-west.

A.29 Sound exposure level 50km/h Mic2 North-west

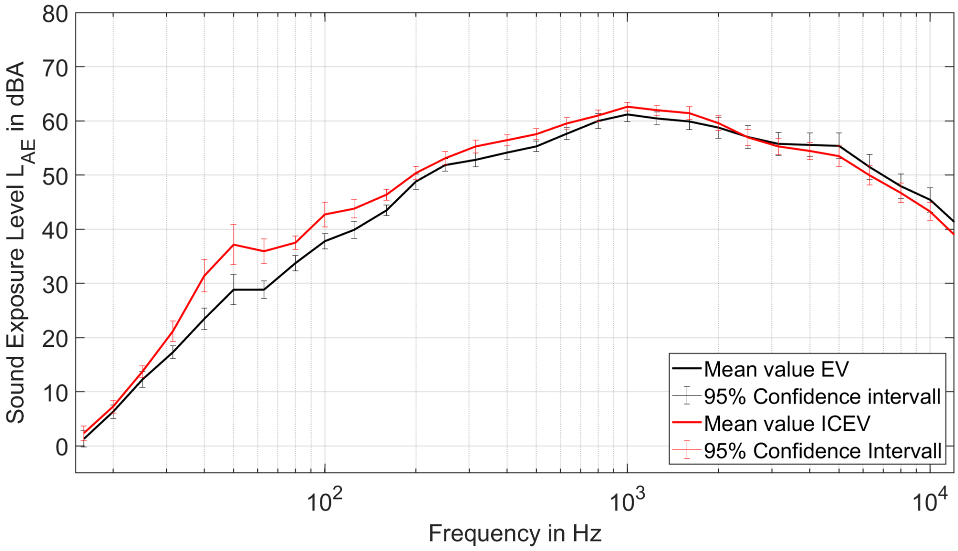


Figure A.29: L_{AE} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 2 at north-west.

A.30 Sound exposure level 50km/h Mic1 South-east

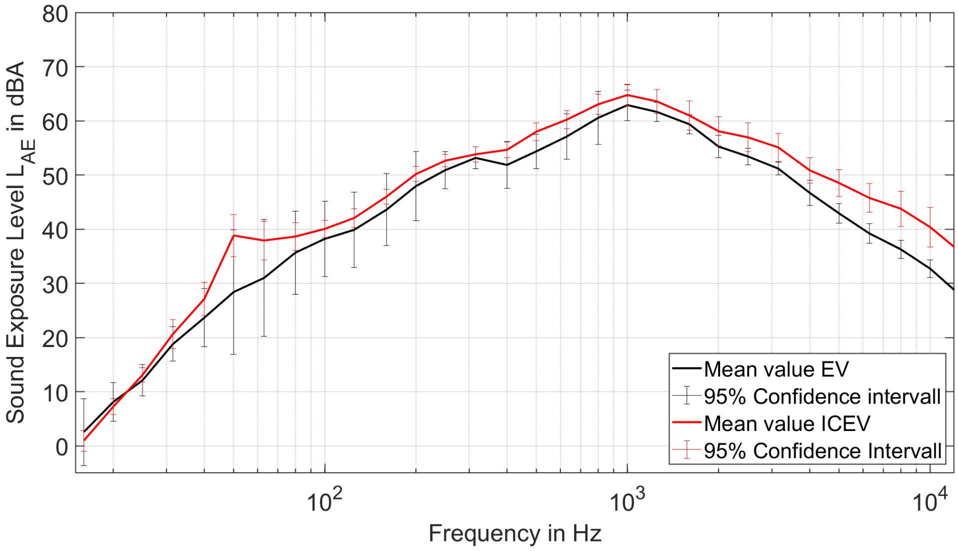


Figure A.30: L_{AE} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 1 at south-east.

A.31 Sound exposure level 50km/h Mic2 South-east

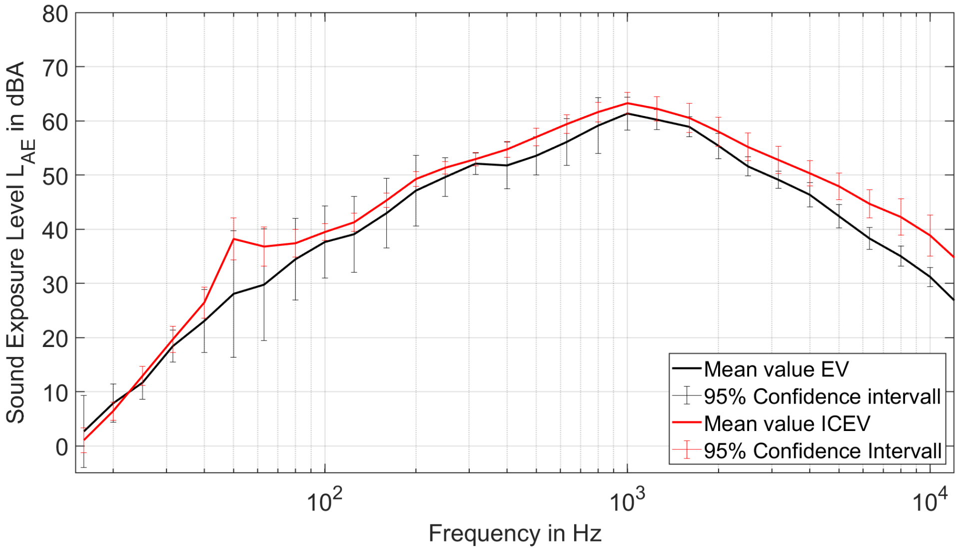


Figure A.31: L_{AE} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 2 at south-east.

A.32 Maximum sound pressure level 50km/h Mic1 Northwest

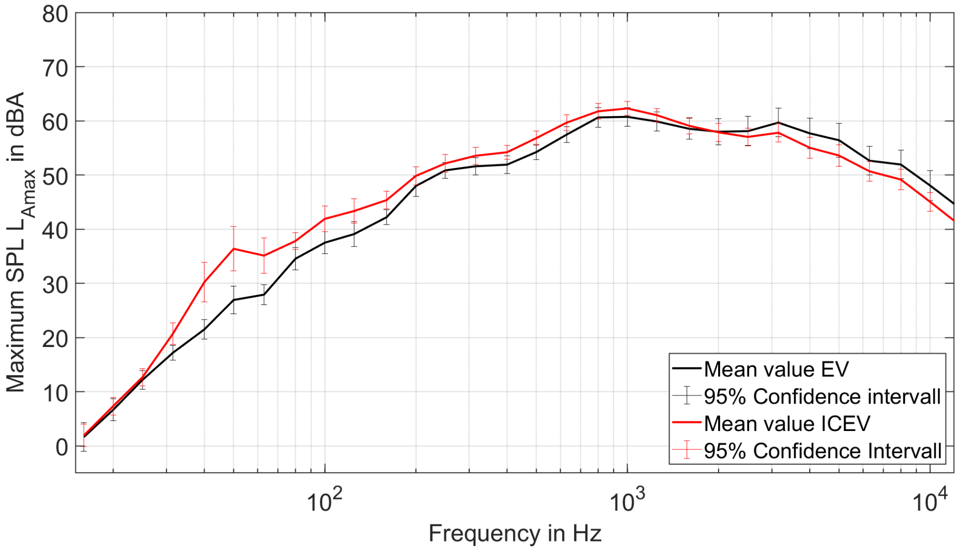


Figure A.32: L_{Amax} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 1 at north-west.

A.33 Maximum sound pressure level 50km/h Mic2 Northwest

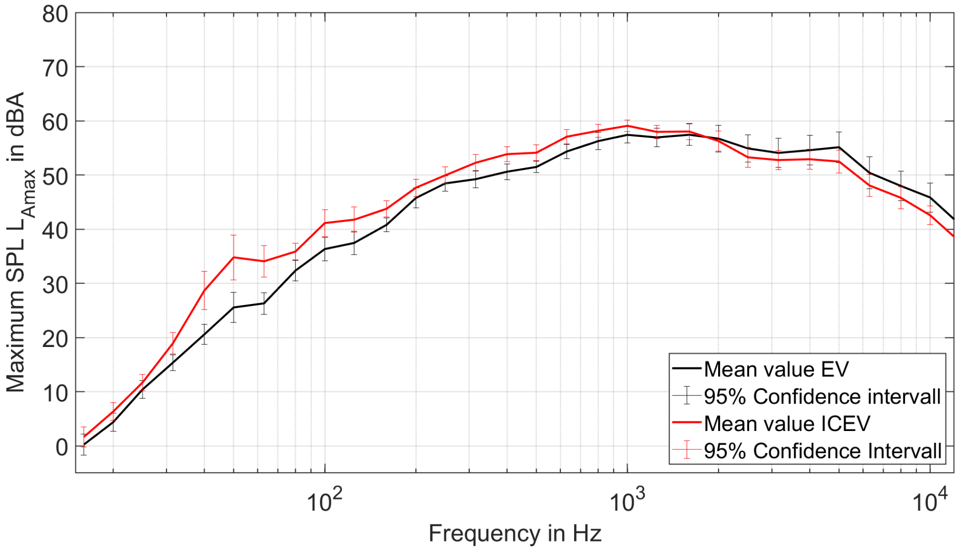


Figure A.33: L_{Amax} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 2 at north-west.

A.34 Maximum sound pressure level 50km/h Mic1 Southeast

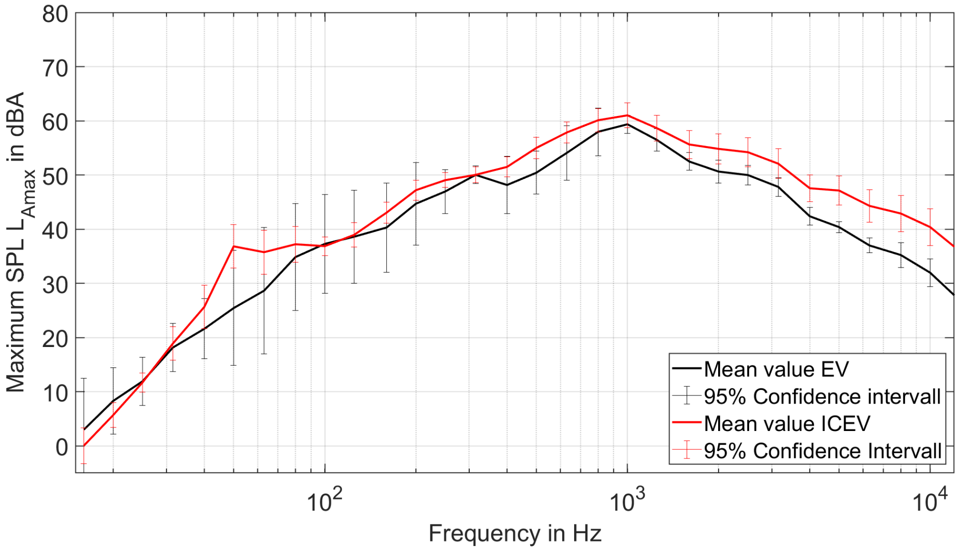


Figure A.34: L_{Amax} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 1 at southeast.

A.35 Maximum sound pressure level 50km/h Mic2 Southeast

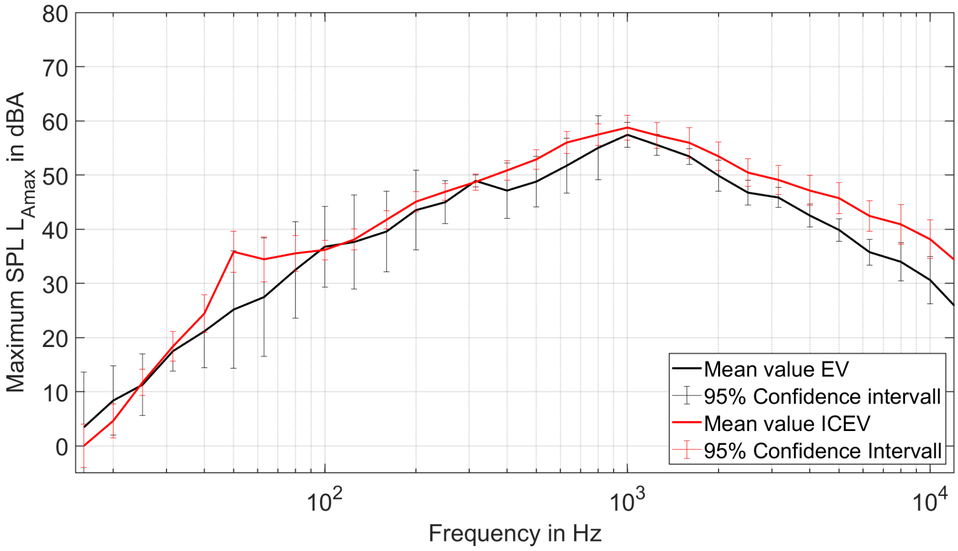


Figure A.35: L_{Amax} compared between EVs and ICEVs and the 95% CI for 50 km/h and microphone 2 at southeast.

A.36 Sound exposure level 60km/h Mic1 North

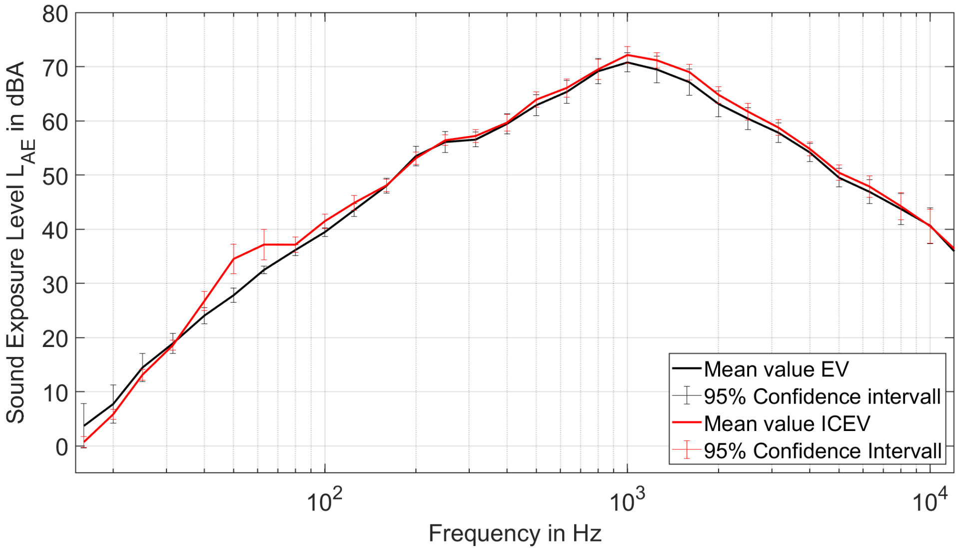


Figure A.36: L_{AE} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 1 at north.

A.37 Sound exposure level 60km/h Mic2 North

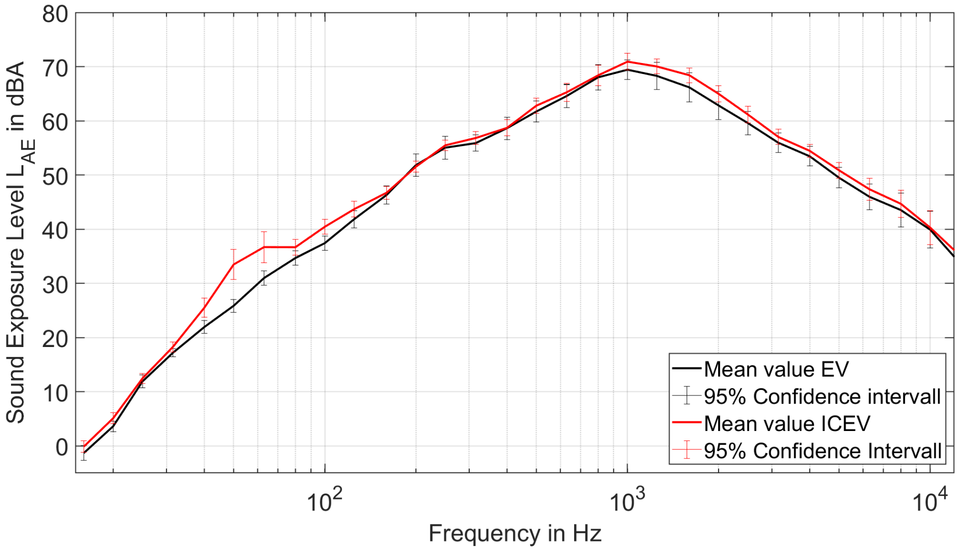


Figure A.37: L_{AE} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 2 at north.

A.38 Sound exposure level 60km/h Mic1 South

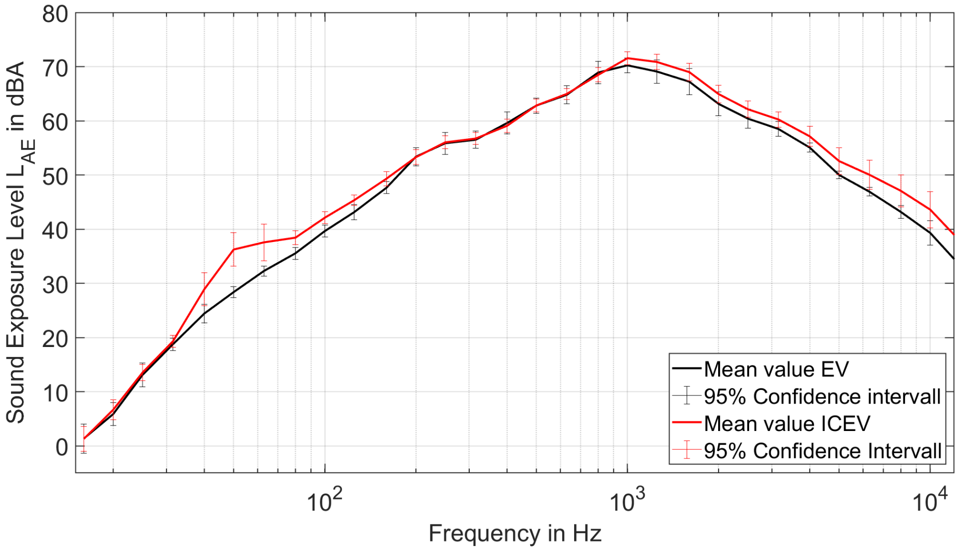


Figure A.38: L_{AE} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 1 at south.

A.39 Sound exposure level 60km/h Mic2 South

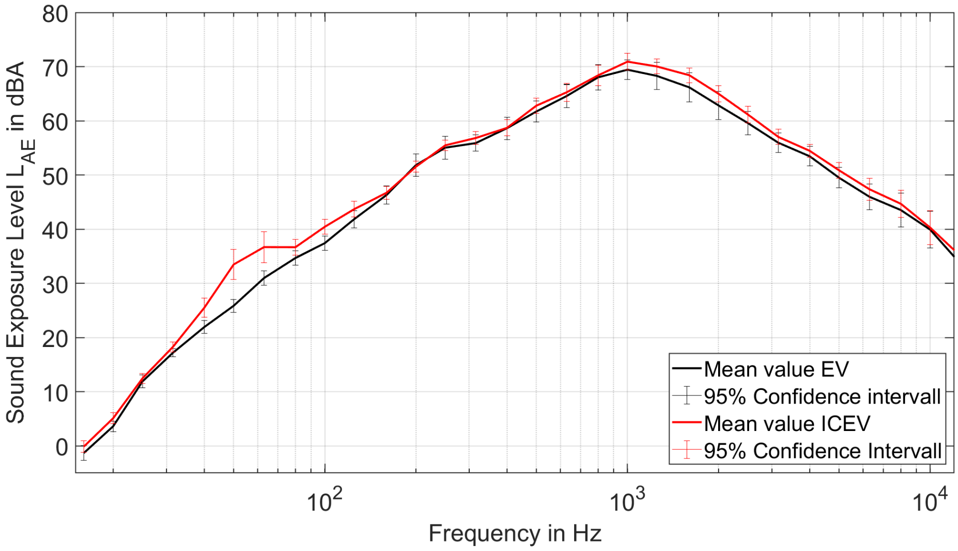


Figure A.39: L_{AE} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 1 at south.

A.40 Maximum sound pressure level 60km/h Mic1 North

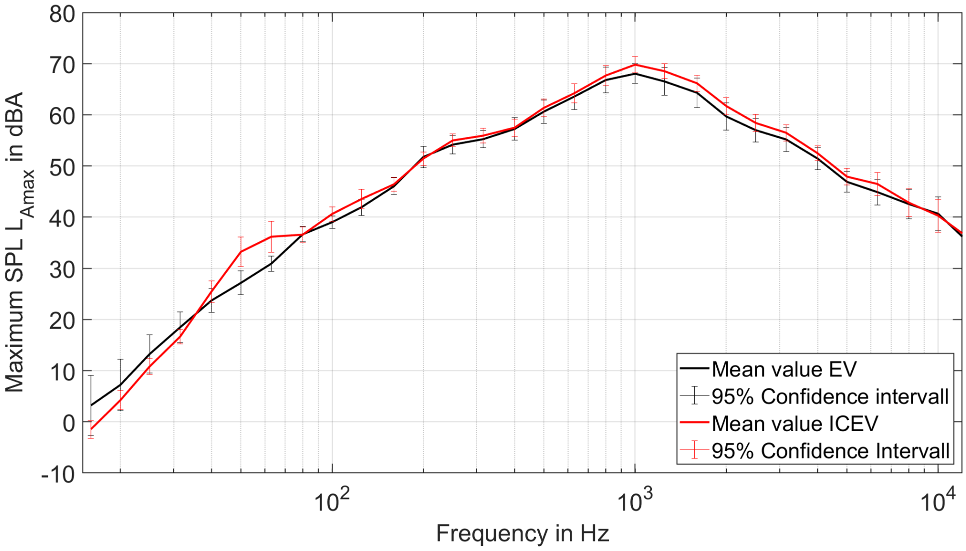


Figure A.40: L_{Amax} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 1 at north.

A.41 Maximum sound pressure level 60km/h Mic2 North

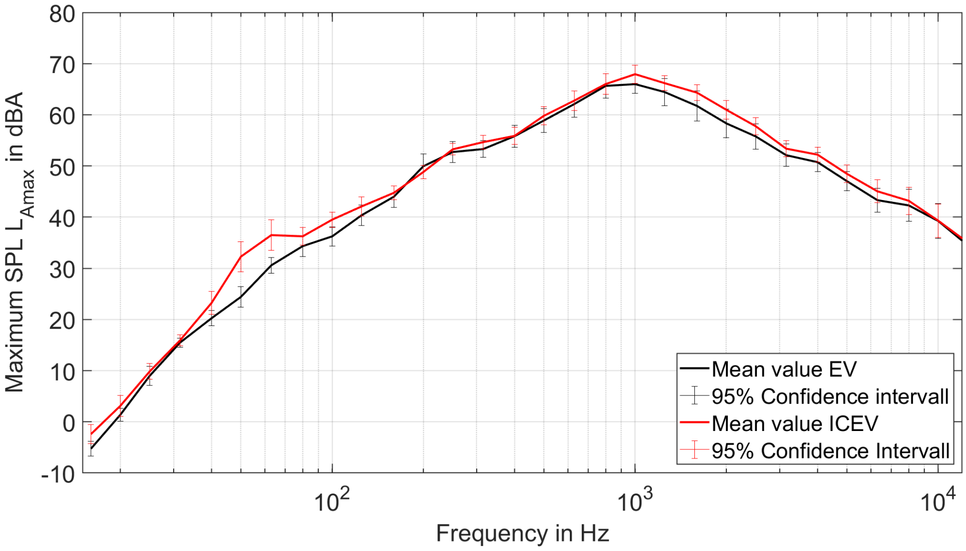


Figure A.41: L_{Amax} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 2 at north.

A.42 Maximum sound pressure level 60km/h Mic1 South

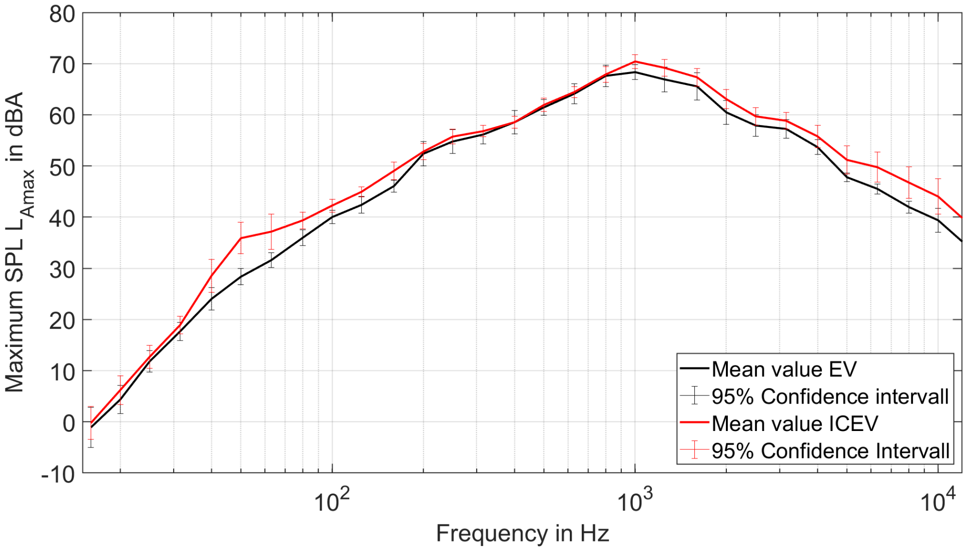


Figure A.42: L_{Amax} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 1 at south.

A.43 Maximum sound pressure level 60km/h Mic2 South

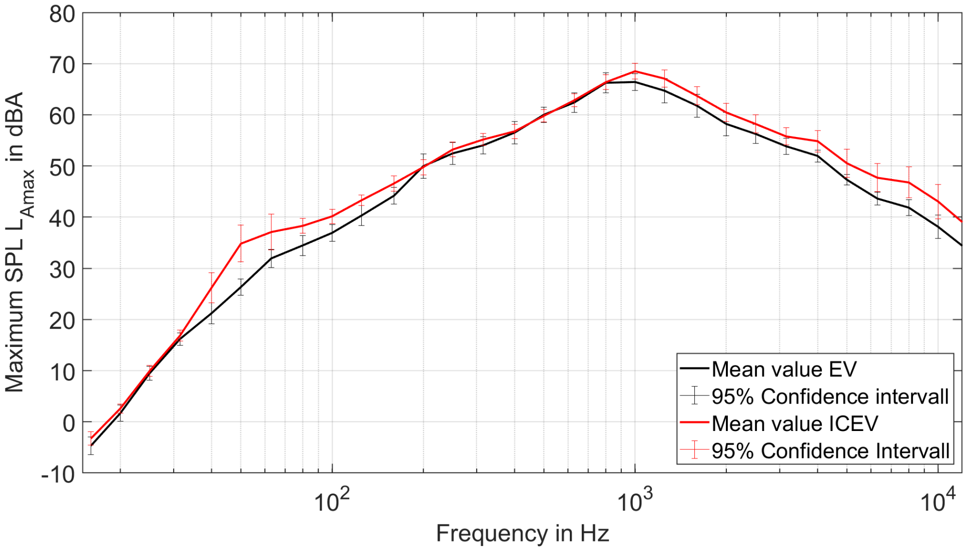


Figure A.43: L_{Amax} compared between EVs and ICEVs and the 95% CI for 60 km/h and microphone 2 at south.

A.44 Linear regression of L_{AE} of EVs for 3 variables

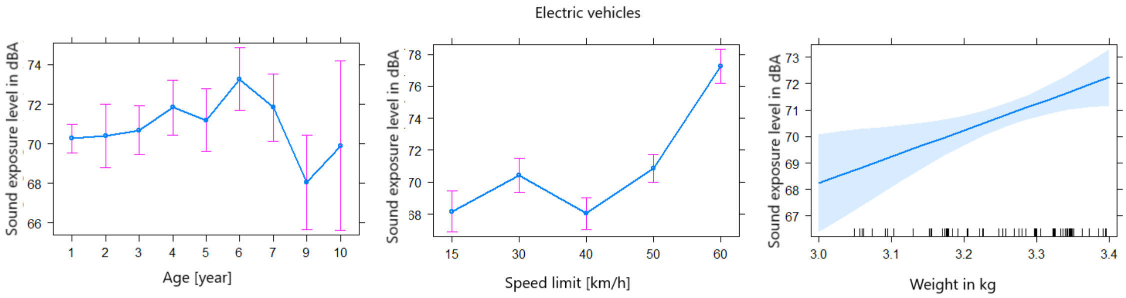


Figure A.44: Linear regression of EVs depending of age, speed limit and weight compared with L_{AE}

A.45 Linear regression of L_{AE} of ICEVs for 3 variables

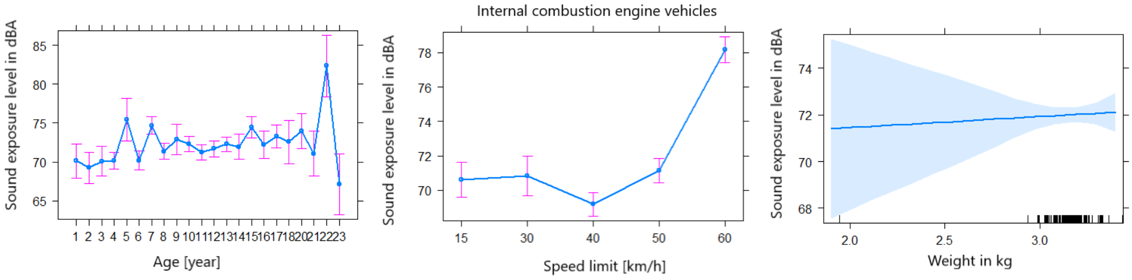


Figure A.45: Linear regression of ICEVs depending of age, speed limit and weight compared with L_{AE}

A.46 Linear regression of L_{Amax} of EVs for 3 variables

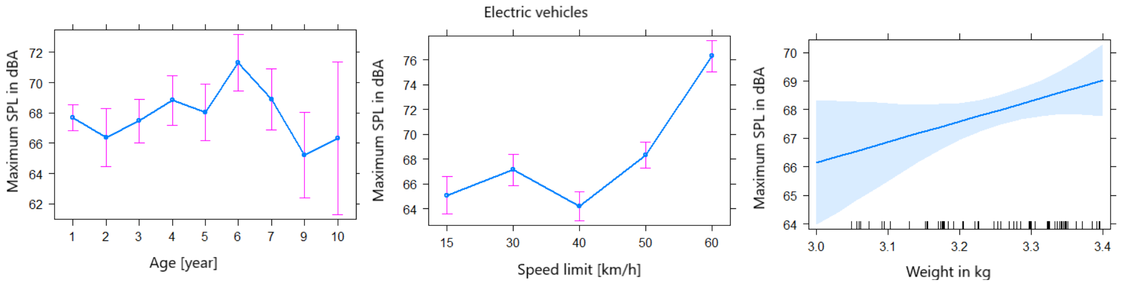


Figure A.46: Linear regression of EVs depending of age, speed limit and weight compared with L_{Amax}

A.47 Linear regression of L_{Amax} of ICEVs for 3 variables

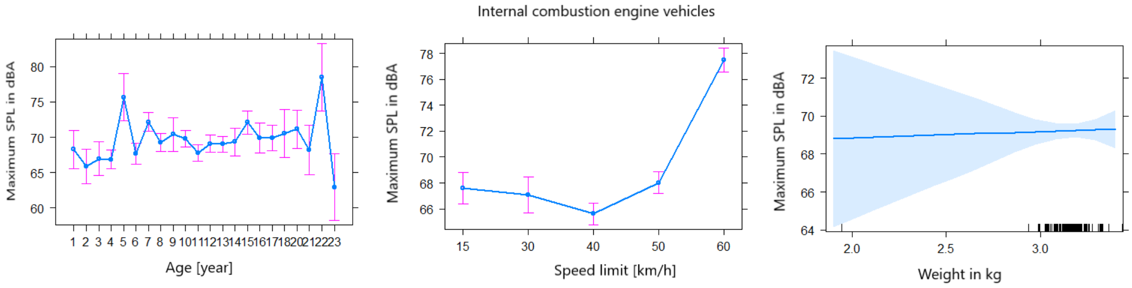


Figure A.47: Linear regression of ICEVs depending of age, speed limit and weight compared with L_{Amax}