Noise from electric vehicles

A literature survey

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Indhold

1. Summary

This literature survey is part of the COMPETT project about electric vehicles and the promotion of their use. It is an international 'state of the art' literature survey that will investigate how much is already known about the noise produced by electric vehicles and maybe discover areas in which more research is needed.

The findings in this literature survey show that there is a potential for noise reduction by replacing ICE vehicles with electric vehicles, but the findings also show that there is a great deal of uncertainty about how large this potential is. The reduction in noise found in the references differs greatly and seems to depend very much on how the comparison between noise from ICE vehicles and electric vehicles is carried out. Most references do, however, confirm the assumption that it is only at low speeds that noise reduction can be expected. However, at what speed this is and what the result would be to noise levels in a city is not clear from the findings.

This report concludes with recommendations on how noise from electric vehicles can be measured in future and on what aspects of this noise need further investigations. These recommendations include investigating the influence different tyres on electric vehicles have and the influence of the surface on which the electric vehicle is driving.

Sammenfatning

Dette litteraturstudie er en del af COMPETT projektet om elbiler og hvordan brugen af disse kan fremmes. Det er et internationalt 'state of the art' litteraturstudie, som vil undersøge, hvor meget der allerede vides om støj fra elbiler og måske afdække, hvor mere forskning er nødvendig.

Resultaterne i denne litteratur undersøgelse viser, at der er et potentiale for støjreduktion ved udskiftning af konventionelle køretøjer med forbrændingsmotorer med elbiler. Men resultaterne viser også, at der er stor usikkerhed om, hvor stort dette potentiale er. Reduktionen af støj i de gennemgåede referencer varierer meget og synes at afhænge meget af, hvordan sammenligningen mellem støj fra konventionelle køretøjer og elbiler er foretaget. De fleste referencer bekræfter dog den antagelse, at det kun er ved lave hastigheder, at en støjreduktion kan forventes. Men ved hvilken hastighed dette er, og hvad det kan betyde for et støjniveau i en by, er ikke entydigt og klart.

Rapporten afsluttes med anbefalinger til, hvordan fremtidige målinger af støj fra elektriske køretøjer kunne tilrettelægges, og udpegning af indenfor hvilke aspekter af støj der er brug for yderligere undersøgelser. Disse anbefalinger inkluderer at undersøge indflydelsen af forskellige dæk, der anvendes på elbiler og indflydelsen af vejbelægningen, det elektriske køretøj kører på.

2. Preface

This report is a part of the project COMPETT (Competitive Electric Town Transport), which is a project financed by national funds which have been pooled together within ERA-NET-TRANSPORT.

In January 2011 ERA-NET-TRANSPORT initiated a range of projects about electric vehicles under the theme ELEKTROMOBILITY+ concerning topics from the development of battery and charging technology to sociological investigations of the use of electric vehicles.

20 European project consortia have now been initiated including the COMPETT project. COMPETT is a co-operation between The Institute of Transport Economics in Norway, The Austrian Energy Agency, The University College Buskerud in Norway, Kongsberg Innovation in Norway and the Danish Road Directorate. The objective of COMPETT is to promote the use of electric vehicles, particularly with focus on private passenger cars. The main question to answer in the project is "How can e-vehicles come in to use to a greater degree?"

This report is an international literature survey about noise emission from electric vehicles, which has been produced as a preliminary investigation leading up to the next phase of measuring the noise emitted from electric vehicles. It will present what is known about noise emitted by electric vehicles and what types of investigations have been conducted on this noise. The results of this literature survey will also be used as a source of inspiration for how to carry out the measurements within COMPETT.

Read more about the project on www.compett.org

The COMPETT project is jointly financed by Electromobility+, Transnova and The Research Council of Norway, FFG of Austria and The Ministry of Science, Innovation and Higher Education (Higher Education Ministry) in Denmark.

Forord

Denne rapport er en del af projektet COMPETT (Competitive Electric Town Transport), som er et projekt finansieret af nationale midler som er samlet i en pulje under ERA-NET-TRANSPORT. ERA-NET-TRANSPORT har i januar 2011 startet et udbud af projekter om el-biler under temaet ELEKTROMOBILITY+ omhandlende emner fra udvikling af batteri- og ladeteknologi samt sociologiske undersøgelser af brug af el-biler. Der er nu igangsat omkring 20 europæiske projektkonsortier herunder COMPETT projektet.

COMPETT er et samarbejde mellem Transportøkonomisk Institut i Norge, Österreichische Energiagentur i Østrig, Høgskolen i Buskerud i Norge, Kongsberg Innovasjon i Norge og Vejdirektoratet i Danmark. Formålet med COMPETT er at undersøge mulighederne for at fremme brugen af elektriske køretøjer, især med fokus på private personbiler. Det vigtigste spørgsmål, der skal besvares, er "Hvordan kan elektriske køretøjer i højere grad blive anvendt?"

Denne rapport er en international litteraturundersøgelse om støj fra elektriske køretøjer Litteraturstudiet skal bruges som baggrund for at vurdere om der er brug for yderligere målinger og analyser af støj fra elektriske køretøjer. Rapporten vil afdække, hvad der vides om støj fra elektriske køretøjer og hvilke typer undersøgelser, der er blevet lavet af denne støj. Resultaterne fra denne litteraturundersøgelse vil også blive brugt som inspiration ved tilrettelæggelse af støjmålinger som planlægges gennemført i COMPETT.

Læs mere om projektet på hjemmesiden www.compett.org

COMPETT projektet er finansieret af Electromobility+, Transnova og Forskningsrådet I Norge, The Austrian Research Promotion Agency (FFG) i Østrig og Ministeriet for Forskning, Innovation og Videregående Uddannelse i Danmark.

4. Introduction

This literature survey is part of the COMPETT project about electric vehicles and the promotion of their use. It is a literature survey of the 'state of the art', which is being produced as part of the preparations for measuring the noise emitted from electric vehicles.

In recent years, the number of electric cars in cities has started to grow. Besides the benefit of being able to reduce environmental pollution (CO_2 and air pollution), there is also a possibility that they can help to reduce the noise pollution, since electric vehicles in general are assumed to be very quiet vehicles. It is therefore interesting to investigate whether this assumption is true and if it is, by what extent are electric vehicles more quiet. This study is an international 'state of the art' literature survey that will investigate how much is already known about the noise produced by electric vehicles and maybe discover areas in which more research is needed.

4.1 Background

The noise from vehicles comes mainly from two different sources, the propulsion and the contact between the tyres and the road. The tyre/road noise increases more with increasing speed than the propulsion noise, and therefore the tyre/road noise dominates the propulsion noise at high speeds. Figure 1 illustrates this by showing the propulsion noise, the tyre/road noise and the total noise from a passenger car as a function of speed calculated with the Nord2000 model. This means that if the tyres used on electric vehicles are the same as on conventional vehicles with internal combustion engines (ICE vehicles), it is expected that it will only be at low speeds that the electric vehicles emit a lower noise level than the conventional vehicles. Even if the noise reduction is only for low speeds, then it can still be of importance in cities as the travelled speed there is often low. In cities there is also a lot of acceleration, deceleration and braking, so if

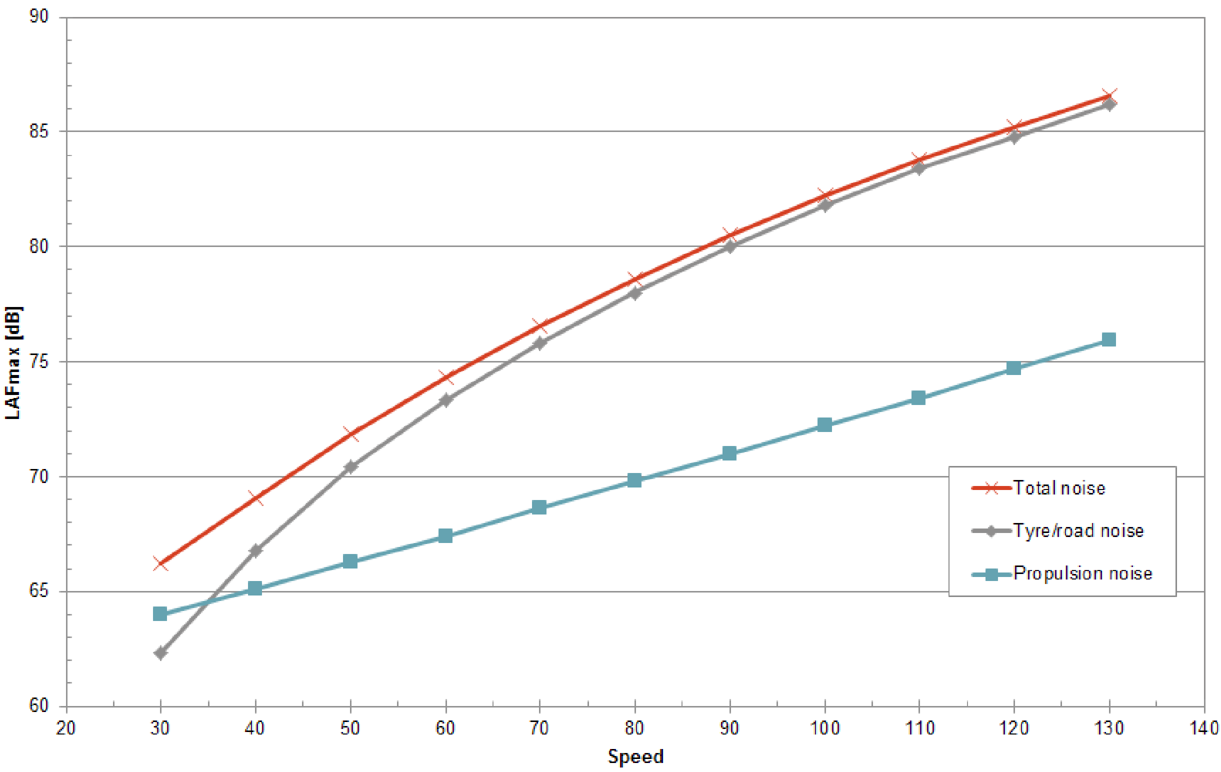

Figure 1:
The propulsion noise, the tyre/road noise and the total noise from a passenger car calculated with the Nord2000 noise prediction model [1].

the electric vehicles are quieter in these situations, then it can also result in a reduction in the noise level.

Furthermore, there may be some other factors about the noise produced by electric vehicles that need attention. If the frequency content of the noise from electric vehicles for instance is different than that of the noise from ICE vehicles it can influence the way the noise is perceived. It has also been reported that some electric motors emit noise-containing single frequency tones, which can be perceived as annoying.

In consideration of the safety of pedestrians and cyclists, adding artificial noise to some electric vehicles in some driving and speed situations has been debated. If noise is to be added to electric vehicles, this noise should also be taken into consideration when measuring and evaluating the noise level from electric vehicles. This literature survey does not focus on investigations into traffic safety related to electric vehicles.

4.2 Research questions

As there are many different aspects to noise from electric cars, a decision needed to be made on what the focus of the literature survey should be. It was therefore decided to focus the literature survey on the following ten questions.

1. Do electric vehicles make more or less noise than conventional vehicles with internal combustion engines?

2. How great is the difference between how much noise different electric vehicles make?

3. What is known about noise from electric vehicles at different speeds?

4. What is known about noise from electric vehicles on acceleration and braking?

5. Does the difference in the tyres on electric vehicles and conventional vehicles with combustion engines make a difference in the noise emitted?

6. What is known about tyre/road noise compared to engine noise from electric vehicles?

7. What is known about the differences in frequency spectrums of the noise from electric vehicles compared to conventional vehicles with combustion engines under different driving conditions (speed and acceleration)?

8. What impact does noise which is artificially added to electric vehicles have on the total noise emission from electric vehicles?

9. How great an impact can replacing combustion engine vehicles with electric vehicles have on the overall noise level in cities?

10. What is the noise emission from hybrid vehicles with both a combustion engine and an electric motor?

5. Method

The search for relevant literature was carried out with the help of a librarian from the Danish Road Directorate (DRD).

Searches were done in the TRID database, which is an integration of the Transportation Research Information Services (TRIS) Database and the Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. Based on the research questions, some keywords were chosen for the searches. The following keywords were used:

- Electric vehicles and noise
- Hybrid vehicles and noise
- Electric vehicles and frequency spectrum
- Electric vehicles and engine noise
- Electric vehicles and tyre noise
- Electric vehicles and tyre noise
- Electric vehicles and road noise
- Electric vehicles and sound emission
- Electric vehicles and noise reduction
- Quiet vehicles
- Electric vehicles and sound
- Electric vehicles and measurements

Furthermore, the proceedings from some relevant conferences in which researchers of the Danish Road Directorate had participated were searched. This included the proceedings from Inter.noise conferences held in 2001 in The Hague, in 2007 in Istanbul, in 2010 in Lisbon and in 2012 in New York.

Other members of the COMPETT project consortium also contributed with relevant literature.

All the lists of references to the material found in the initial searches were looked through in order to discover more relevant material.

6. Nomenclature

ICE = internal combustion engine

Engine refers to combustion engine

Motor refers to electric motor

Propulsion noise refers to the noise from either an engine or a motor

Conventional vehicle with combustion engine refers to an ICE vehicle

Tyre/road noise refers to the noise due to the contact between the tyres and the road

Hybrid vehicle = vehicle with both an internal combustion engine and an electric motor

Sound pressure level is a measure for noise level

An A-weighted level is a noise level which has been weighted in a way to better represent the way the noise is perceived by the human ear. This means that some frequencies will influence the overall level more than others.

7. Litterature about noise from electric vehicles

7.1 Passenger cars

A French study from 2001 [2] investigated noise at different speeds with an ICE car, a hybrid car and an electric car. The measurements were taken on an asphalt concrete test track with the microphone 7.5 m from the centre of the track and 1.2 m above the ground as a controlled pass-by measurement. The cars were driven at constant speed when the measurements were performed. This study does not separate the tyre/road noise and the propulsion noise and it should be noted that the ICE car used for comparison runs on diesel and not petrol. The results can be seen in Figure 2, where R1 to R5 stand for different gears. The results show that at very low speeds the noise can be reduced by about 15 dB, but at speeds above 50 km/h the difference is negligible. Furthermore, these results make it clear that the gear a car is driven in has a great influence on the noise. Another interesting observation which can be made is that, as expected, the hybrid car driven in electrically powered mode emits the same level of noise as the purely electric car.

The National Traffic Safety and Environment Laboratory and the Ministry of Land, Infrastructure, Transport and Tourism in Japan have taken an interest in the noise from electric and hybrid vehicles, mostly in order to determine whether these vehicles cause a safety risk to pedestrians due to their low noise level, especially in consideration of visually impaired people. In 2010, they measured the noise from a hybrid vehicle operated in electric mode and from two ICE vehicles for comparison [3]. It is not specified what types of vehicles were used, but later in this study small passenger cars were used to determine the distance at which approaching cars can be heard and it is therefore reasonable to presume that the noise measurements were also done using small passenger cars. The noise measurements were taken with the microphone positioned 2 m from the centre of

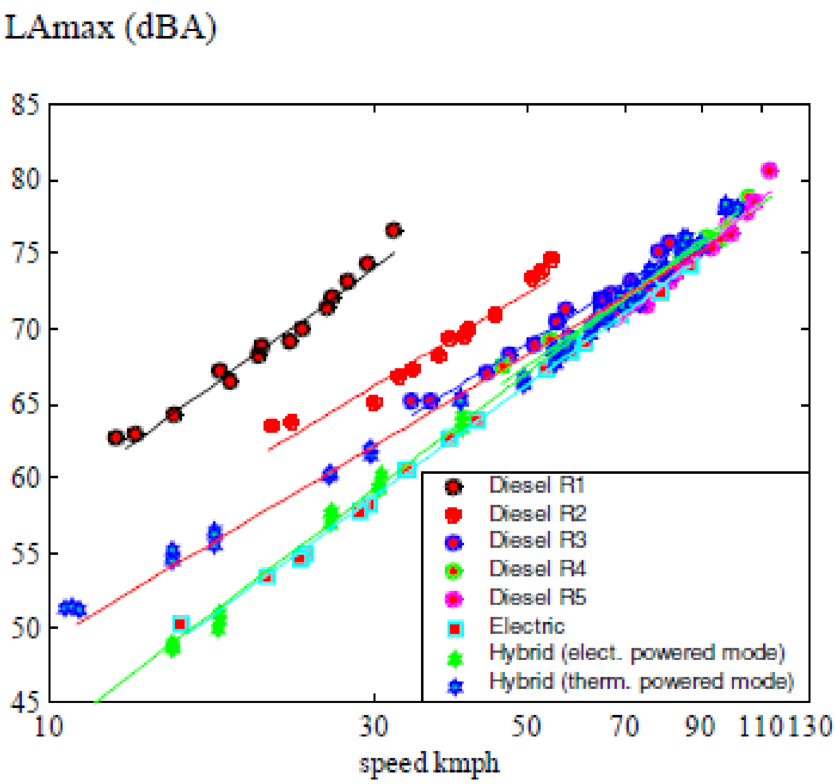

Figure 2:
The maximum noise level from different types of cars measured with pass-by measurements. The microphone was placed 7.5 m from the centre of the cars and 1.2 m above the ground. From a French study by Joël Lelong and Roger Michelet. Presented here with the kind permission of Joël Lelong [2].

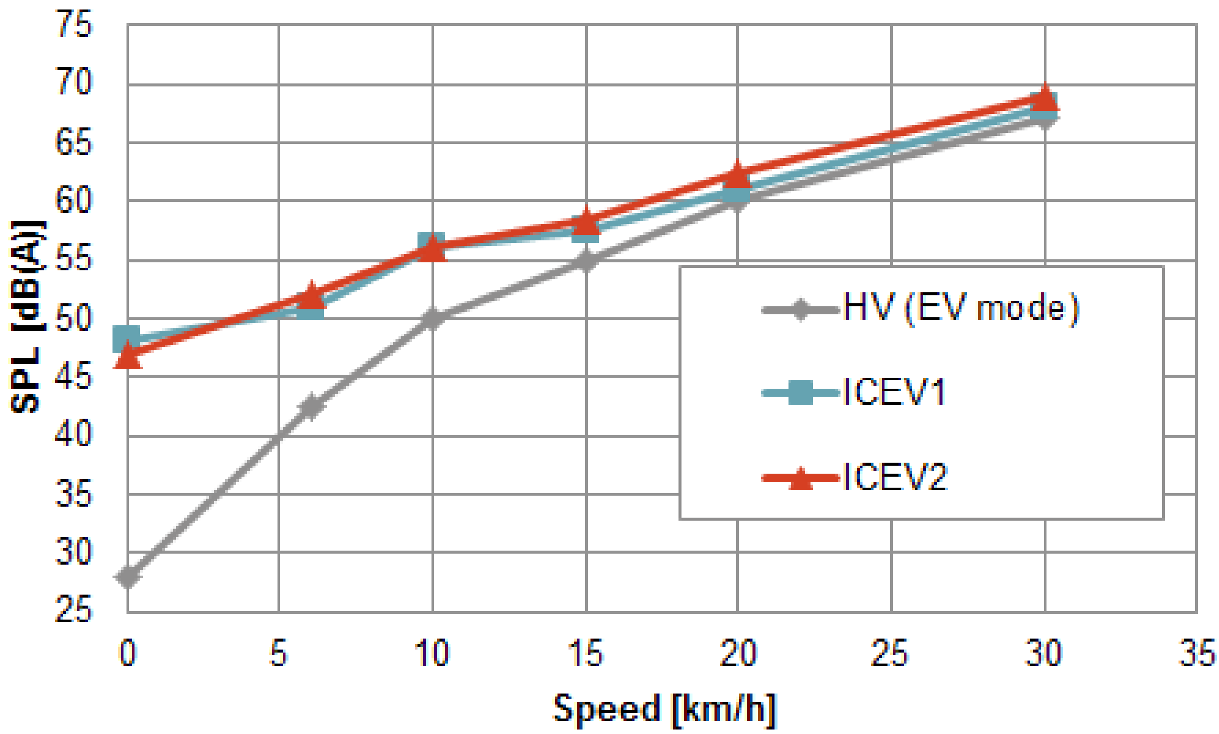

Figure 3:
The maximum sound pressure level from two different ICE vehicles and one hybrid vehicle operated in electric mode when the cars pass-by at different constant speeds with the microphone at a distance of 2 m. Results from a Japanese study [3].

the cars; the height of the microphone is not stated. The cars passed at different speeds and the maximum sound pressure levels were measured. It does not say explicitly whether the cars were driven at constant speeds, but it is assumed that they were. The results of the measurements are shown in Figure 3, where it can be seen that the electric vehicle is only quieter below 20 km/h.

The Japanese study was continued in the following year [4] and measurements of the noise from two electric vehicles (hereafter EV-1 and EV-2), one hybrid vehicle (hereafter HV-1) and two ICE vehicles (hereafter ICE-1 and ICE-2) were carried out. It is not specified what vehicles were used, but it is assumed that they were passenger cars. The measurements also included noise artificially added to the electric and hybrid vehicles. There is no explicit description of the sounds, but they were created following the Japanese guidelines from 2011 that recommend sounds which simulate the sound of ICE vehicles. The measurements were taken on cars passing at constant speeds 2 m from the centre of the track and 1.2 m above the ground. It does not say in the reference but it is assumed that the maximum noise was measured. Table 1 shows the results of the noise measurements when the cars were driven at 10 km/h and at 20 km/h. These measurements show that for 10 km/h without approaching sound there is a 6 dB to 9 dB difference between the ICE cars and the electric cars. At 20 km/h the difference is slightly smaller, 5 dB between EV-2 and the ICE cars, and for EV-1 there is no apparent difference. With the artificially added noise there is no difference in sound pressure level for either of the electric cars and the ICE cars, but there is a difference of 2 dB between the ICE cars and the hybrid car. It is not specified in the reference at what speed the hybrid car switched from electric mode to ICE mode and whether the artificial sound was turned off in the hybrid car when it was driven in ICE mode, but there is no difference between the values for the noise from the hybrid with and without artificial noise, which indicates that no artificial noise was in fact used in the hybrid at 20 km/h.

In an American study from 2012 [5] measurements were taken of the noise emitted by an electric vehicle. The vehicle used was a 2012 Chevrolet Volt, which is a midsize passenger car. Measurements were taken at speeds between 5 mph (8 km/h) and 70 mph (113 km/h) with 5 mph increments and both at constant speed and at full acceleration. The sound pressure level was measured on two different test tracks and at distances of 25 feet (7.6 m) and 50 feet (15.2 m). It is not clear how the measurements from these two positions were handled, but it is expected that they were averaged. The measurements were used to calculate the Reference Energy Mean Emissions Levels (REMEL), which is an American value of standardised sound emission level, which is used to estimate the noise of the vehicle fleet on any road. This is used in the American road noise prediction method. The REMEL curves for the VOLT were then compared to a REMEL curve for a standard ICE car. The results can be seen in Figure 4 and Figure 5. Figure 4 shows that at constant speed there is a difference of around 10 dB at 5 mph in the noise levels and between 15 mph (24 km/h) and 45 mph there is no difference. Rather unexpectedly then, the difference increases again at speeds above 45 mph and at 70 mph there is a difference of around 2 dB. At full acceleration there is a difference of 7 dB at 5 mph and at 25 mph (40 km/h) there is no difference in noise level.

In 2010, The National Highway Traffic Safety Administration in the USA performed some measurements in which the noise from hybrid vehicles was compared to the noise from some similar ICE cars [6]. In the reference these are called 'twin' cars. The two couples of 'twin' cars were a Toyota Matrix (ICE) and a Toyota Prius

Vehicle	10 km/h	20 km/h
EV-1	50 dB	62 dB
EV-1 with artificial sound	55 dB	62 dB
EV-2	47 dB	57 dB
EV-2 with artificial sound	56 dB	62 dB
HV-1	50 dB	60 dB
HV-1 with artificial sound	54 dB	60 dB
ICE-1	56 dB	62 dB
ICE-2	58 dB	62 dB

Table 1:
The A-weighted sound pressure level from pass-by measurements of two electric cars and two ICE cars. The microphone was placed 2 m from the centre of the track and 1.2 m above the ground [4].

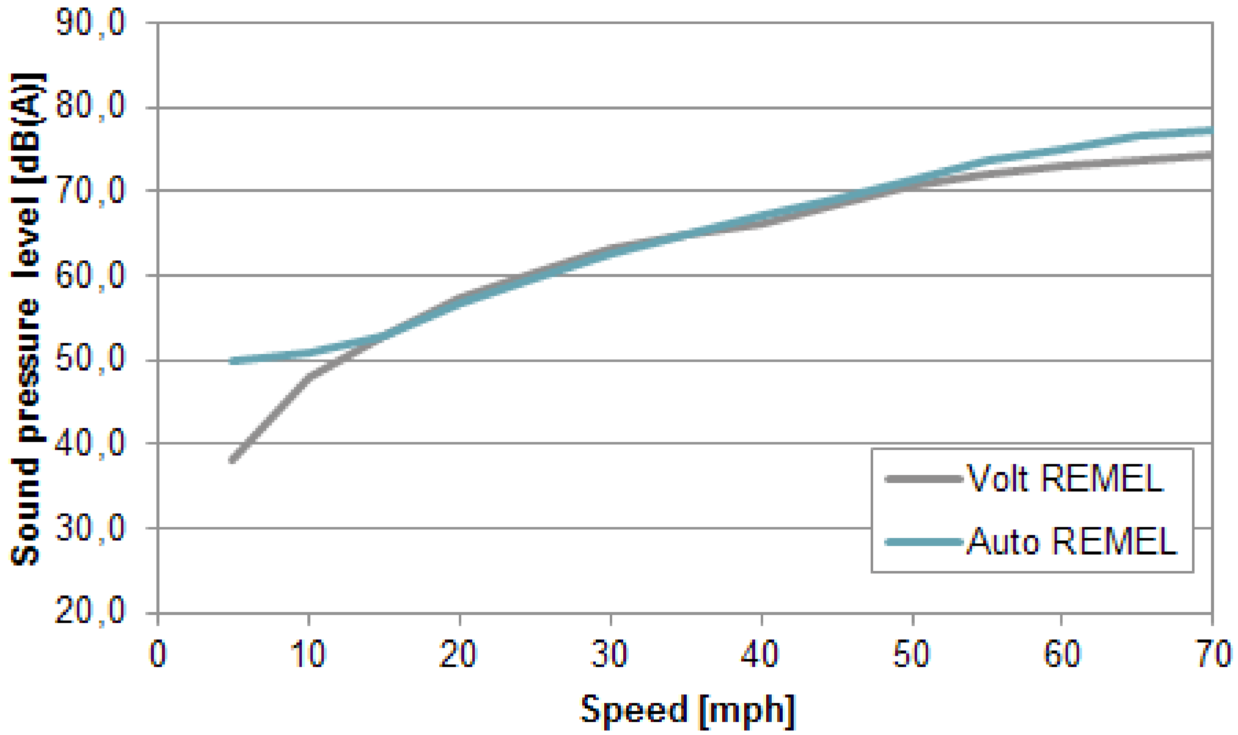

Figure 4:
The REMEL (an American value of standardised sound emission level) curves and the measured data for the sound emission from an electric car and a standard ICE car at constant speeds. [5].

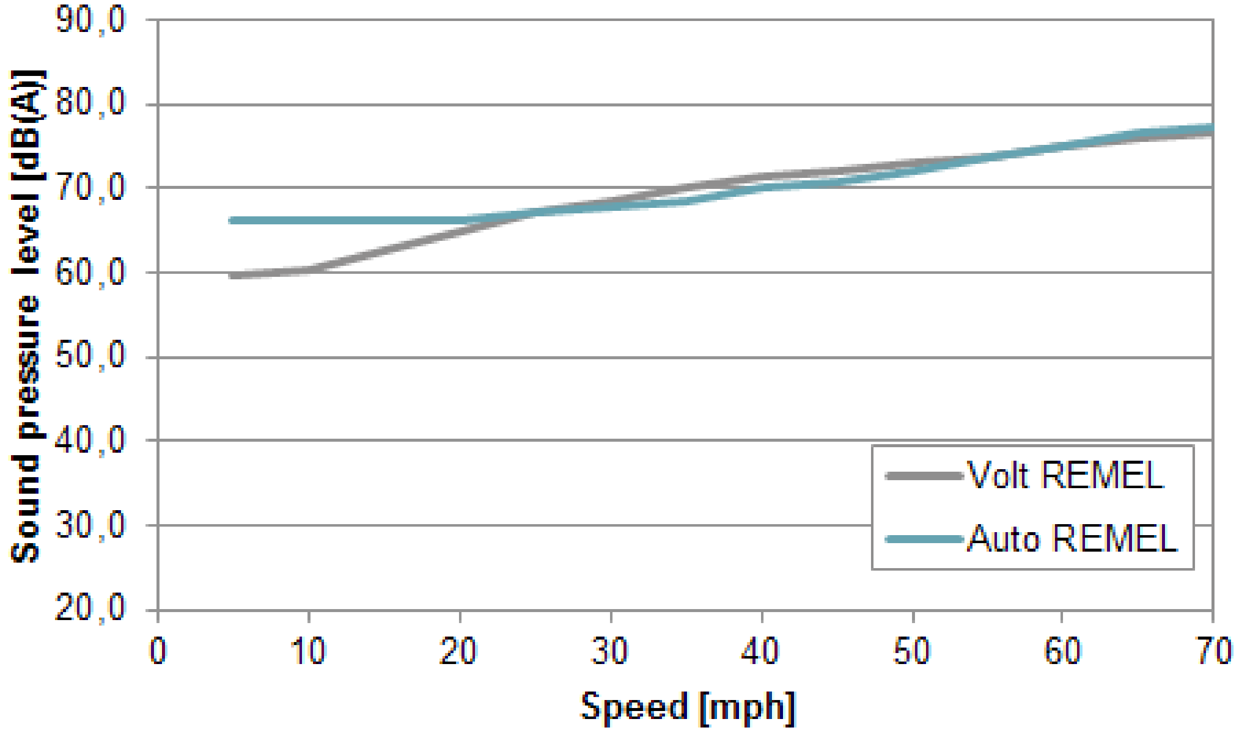

Figure 5:
The REMEL (an American value of standardised sound emission level) curves and the measured data for the sound emission from an electric car and a standard ICE car at full acceleration [5].

(hybrid) along with an ICE Toyota Highlander and a hybrid Toyota Highlander. The Matrix and the Prius are midsize passenger cars and the Highlanders are midsize SUVs. The results presented here only include the hybrid cars driven in electric mode. The main aim of the study was to investigate whether or not artificial sound needed to be added to electric or hybrid vehicles and what these sounds could be. The measurements were taken as pass-by measurements 3.7 m from the centre of the track and 1.5 m above the ground. The speeds studied were 6 mph (9.7 km/h), 10 mph (16.1 km/h), 20 mph (32.2 km/h), 30 mph (48.3 km/h) and 40 mph (64.4 km/h). The results can be seen in Figure 6 and Figure 7, which show that the Prius is more silent than its 'twin', the Matrix at 6 mph and that the difference in noise from the two Highlanders is not particularly great. For both figures it can be said that at 30 mph and above the noise from the hybrid cars and the ICE cars converge. The reason why the idle noises are not included for the hybrid cars is that the levels were too low to be measured accurately. The noises from the cars were also measured when they were driving in reverse at 5 mph (8 km/h) and the method of measuring was the same as when the cars were driving forward. The results can be seen in Table 2. Furthermore, the noise from the cars when accelerating and decelerating was measured. In the accelerating situation the cars accelerated from 20 mph (32 km/h) 200 feet (61 m) from the microphone. It is stated that the acceleration was kept constant, but it is not stated what the acceleration was. In the decelerating situation the cars started braking from 20 mph at a constant deceleration of 1 m/s2 100 feet (30 m) from the microphone, making the speed at the microphone 10 mph. The results for acceleration and deceleration can also be seen in Table 2. From the table it can be seen that the difference between the noise from the hybrid cars and their ICE 'twins' driven in reverse is 6.7 dB for the Prius and the Matrix and 4.5 dB for the Highlanders. At acceleration there is a difference of 0.5 dB within one of the 'twin' pairs and none within the other pair. At deceleration the difference between the Prius and the Matrix is 1.9 dB, the hybrid Prius driven in electric mode being the noisiest, and the difference between the hybrid Highlander and the ICE Highlander is 4.5 dB, the ICE being the noisiest.

Vehicle type	Reverse	Acceleration	Deceleration
Prius (hybrid in electric mode)	44,8 dB	63,1 dB	53,4 dB
Matrix (ICE)	51,5 dB	63.6 dB	51.5 dB
Hybrid Highlander (electric mode)	48.6 dB	65 dB	48.6 dB
ICE Highlander	53.1 dB	65 dB	53.1 dB

Table 2:
The maximum sound pressure levels from four different cars driven in reverse at 5 mph (8 km/h), at acceleration and at deceleration. Measured 3.7 m from the centre of the track and 1.5 m above the ground. From a study by The National Highway Traffic Safety Administration in the USA [6].

In 2012, a Master's thesis from The Technical University of Denmark also looked at the subject of noise from electric cars [7]. In this project controlled pass-by measurements were taken of the noise from a small electric passenger car and an ICE car of similar type and dimensions. The cars were an electric Citroën C1 and a Toyota Aygo with a petrol engine. The tyres were changed from one car to the other, so exactly the same tyres were used for the measurements. The measurements were taken both at different constant speeds and at accelerations from different speeds and the microphone was placed 7.5 m from the centre of the track and 1.2 m above the ground. The type of asphalt on the test track was estimated to be asphalt concrete with 11 m stone size (AC11). The results of the measurements can be seen in Figure 8 and Figure 9. These results show differences in noise from electric cars and ICE cars up to 80 km/h. The difference is greater at lower speeds, but it is still over 2 dB for a constant speed of 80 km/h. This is an unexpected result for this study as the electric car and the ICE car were very similar cars of almost the same dimensions and weight and they were equipped with the same tyres, so the tyre/road noise would be expected to be the same. Figure 9 shows the noise levels from the cars at acceleration from different speeds. The speeds on the x-axis are the constant speeds the cars are driven at before acceleration and the levels shown are means of the noise levels measured at the beginning of the acceleration and after 10 m of acceleration. It can be seen that the difference in noise from the electric car and the ICE car is greater when the cars are accelerating. The difference is as great as around 7 dB and when the cars accelerate from 70 km/h the difference is almost 4 dB.

An Austrian study from 2009 [8] involved measuring the sound pressure level of electric cars together with the sound pressure level of the noise from ICE cars. 20 different cars were used from both categories. It is not stated exactly what cars were used, but it is stated that

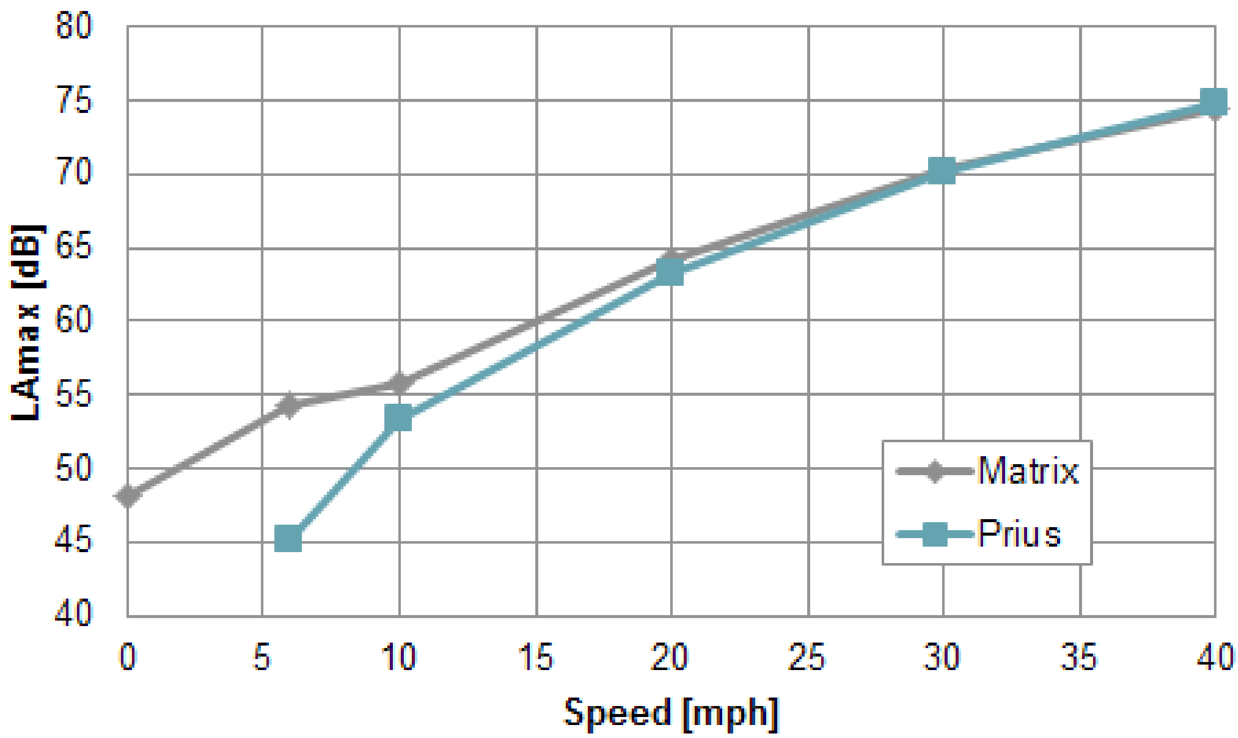

Figure 6:
The noise from a Toyota Prius (hybrid car driven in electric mode) and its 'twin' Toyota Matrix (ICE car) measured as pass-by 3.7 m from the centre of the track. From a study by The National Highway Traffic Safety Administration in the USA [6].

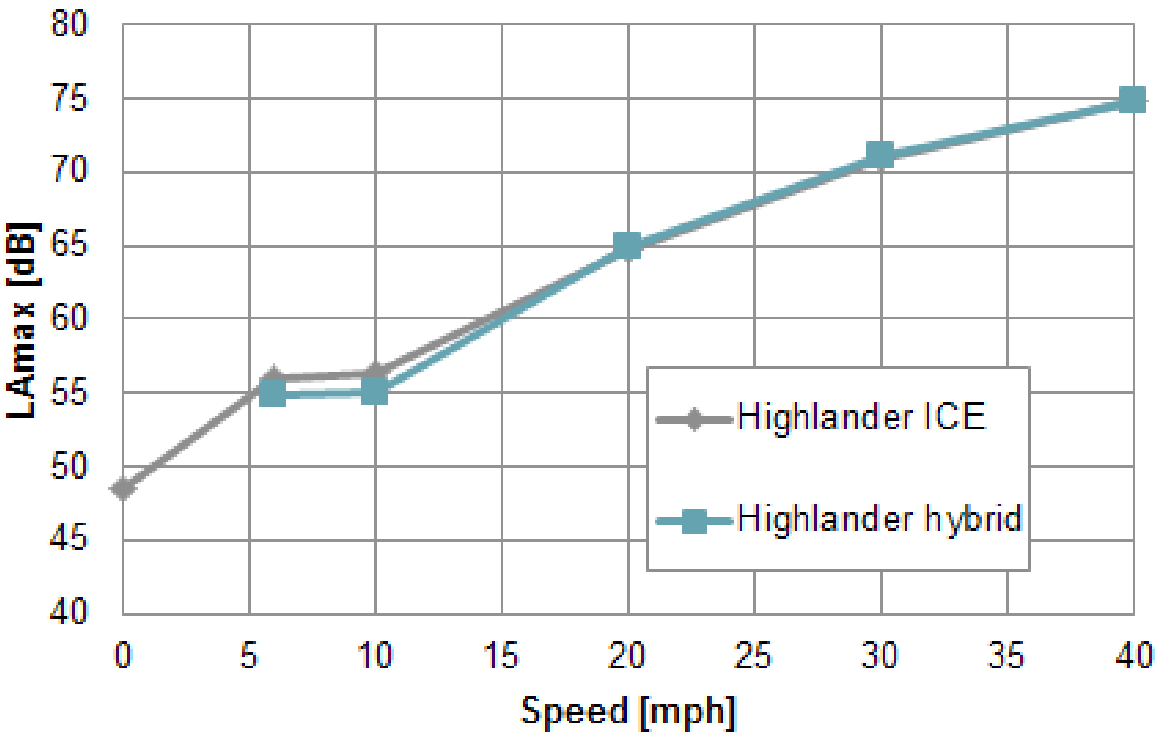

Figure 7:
The noise from a Highlander Hybrid (driven in electric mode) and its 'twin' Highlander ICE measured as pass-by 3.7 m from the centre of the track. From a study by The National Highway Traffic Safety Administration in the USA [6].tric car and a standard ICE car at full acceleration [5].

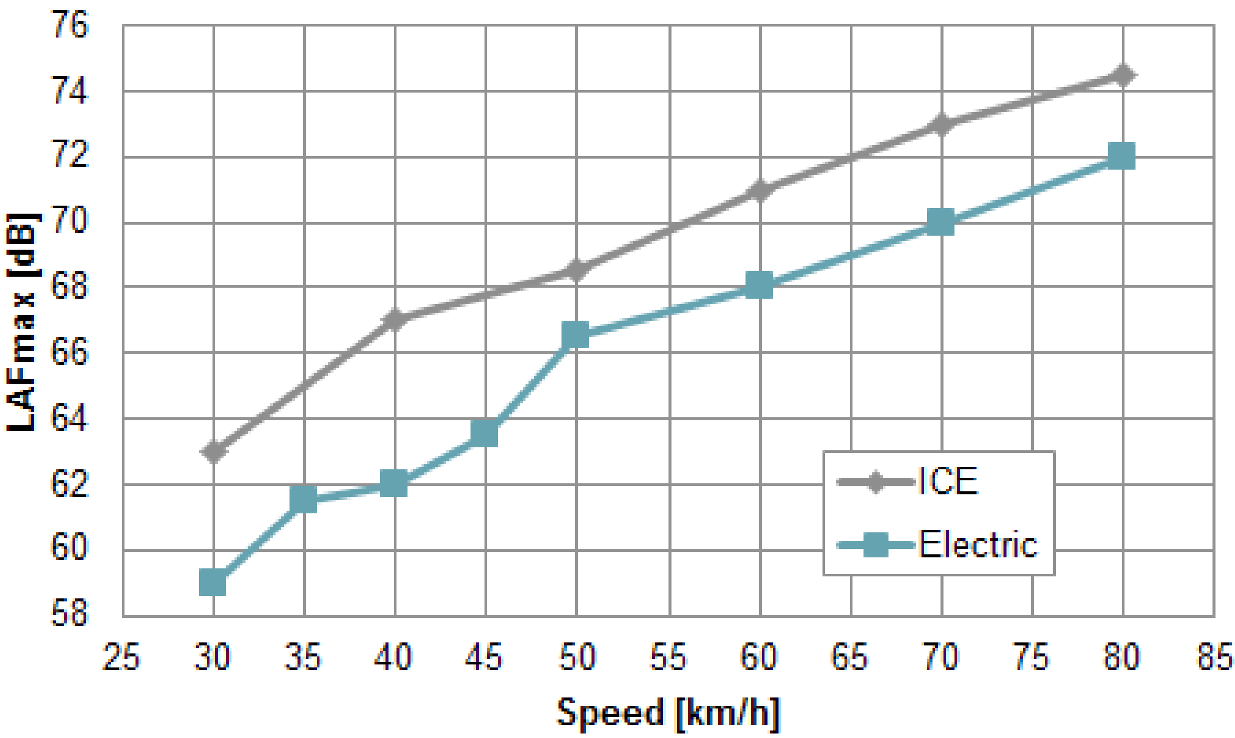

Figure 8:
Maximum noise levels from an electric car and an ICE car passing by at constant speeds from a Danish Master's thesis [7].

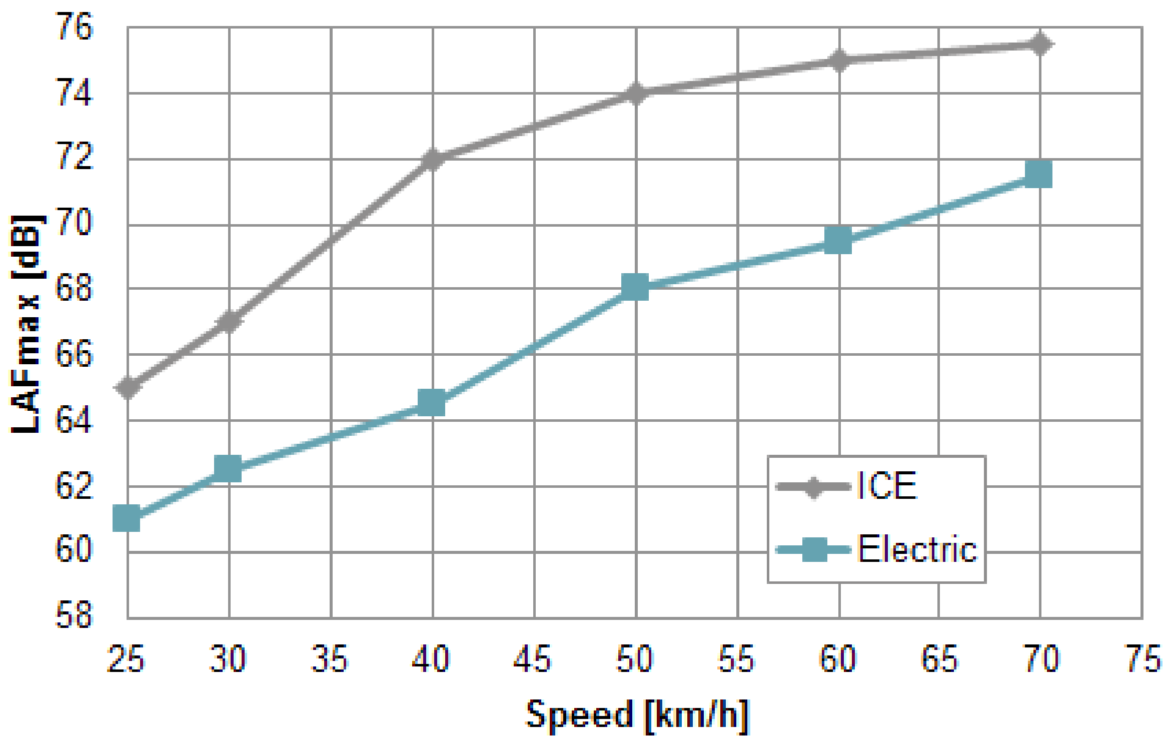

Figure 9:
Noise levels from an electric car and an ICE car accelerating from different speeds from a Danish Master's thesis [7].

they were different types and sizes, including both diesel and petrol engines. Off-road vehicles were also included in the ICE group. It is not clear what types of electric cars were used. The microphone was placed 15 m from the centre line between the two tracks and 1.8 m above the ground. Measurements were taken at 30 km/h, 50 km/h and in stop-and-go situations. It is not specified how the stop-and-go measurements were carried out. Ten cars moved in each direction of the test track for each measurement and each measurement was taken using all electric cars or all ICE cars. The result was that the noise from the electric cars was 4 dB lower at 30 km/h, 3 dB lower at 50 km/h and 8 dB lower for the stop-and-go situation.

In 2011, The University of Duisburg-Essen in Germany [9] measured the noise from 3 different electric cars and 4 different ICE cars, one of which was a diesel car and 3 of which were petrol cars. The maximum sound pressure level was measured with the microphone placed 7.5 m from the track and with the cars driving at 30 km/h. The results can be seen in Table 3, where it is also specified what cars were used. The German E-Cars Stromos is comparable to the Opel Agila and naturally the Smart Fortwo cars are also comparable. The Smart cars are very small cars that only have two seats and the other cars are also quite small passenger cars, however they have four seats. The Stromos is the quietest electric car and the Agila is the quietest ICE car, and the difference between the two is 2 dB. The difference between the electric Smart car and the petrol Smart car is 3.5 dB and the difference between the electric Smart car and the diesel Smart car is 4.5 dB. The electric cars are no more than 1 dB apart, while the ICE cars are up to 3.5 apart including the diesel car and up to 2.5 dB excluding the diesel car. The lowest noise level of all is 57 dB and the highest is 62.5 dB, giving a difference of 5.5 dB. The Agila and the Stromos were also used for subjective tests on how the vehicle noise is perceived by people, and the results of these are presented in Section 7.5.

The EU project CityHush is a project that looks at reducing transport noise in cities [10]. One of the ideas of

Vehicle	Speed and gear	Sound pressure level [dB]
German E-Cars Stromos (electric)	30km/h	57.0
Mega E-city (electric)	30km/h	57.5
Smart Fortwo (electric)	30km/h	58.0
Opel Agila (petrol)	30km/h (2nd gear)	59.0
Ford Fiesta (petrol)	30km/h (2nd gear)	60.5
Smart Fortwo (petrol)	30km/h (2nd gear)	61.5
Smart Fortwo (diesel)	30km/h (2nd gear)	62.5

Table 3:
Sound levels from 3 electric cars and 4 ICE cars driving at constant speed. Measured 7.5 m from the track [9].

Vehicle	Electric motor	Kerb weight	Tyres
Toyota Prius (hybrid)	50 kW, 400 Nm	1400 kg	Primacy Pilot 195/55 R16
Mitsubishi iMiEV	47 kW, 180 Nm	1120 kg	Dunlop Enasave Front: 145/65 R15 Rear: 175/55 R15
Fiat 500 EV adapt	24 kW (nominal)	1100 kg	Continental ContiEcoContact 3 175/65 R14
Peugeot iOn	47 kW, 180 Nm	1120 kg	Dunlop Enasave Front: 145/65 R15 Rear: 175/55 R15
Citroën C-Zero	47 kW, 180 Nm	1120 kg	Dunlop Enasave Front: 145/65 R15 Rear: 175/55 R15
Fiat 500 Liion	30 kW (nominal) 60 kW (peak)	Not stated	Dunlop Duratech 175/65 R14

Table 4
Specifications of the cars used in reference [10].

the project is to introduce quiet zones (Q-zones), where vehicles will have to observe strict restrictions on the noise they emit. In order to determine what the noise limits should be the noise from different electric vehicles was measured. The electric cars which were used were all passenger cars and all types but one were small. The specifications of the cars can be seen in Table 4.

The measured noise from the electric vehicles was then compared to noise data collected from different ICE vehicles. All measured and collected data was measured in accordance with the SPB standard ISO 362-1:2007, which means that the measurements were taken 7.5 m from the road and 1.2 m above the ground. Figure 10 shows the average of the noise levels from each type of car. Lcrs is the noise from the cars driven at a constant speed of 50 km/h, Lwot is the noise from the cars at full acceleration from 50 km/h and Lurban is the logarith-mic average of the previous two. Lurban is a parameter invented by the authors of the reference as an attempt

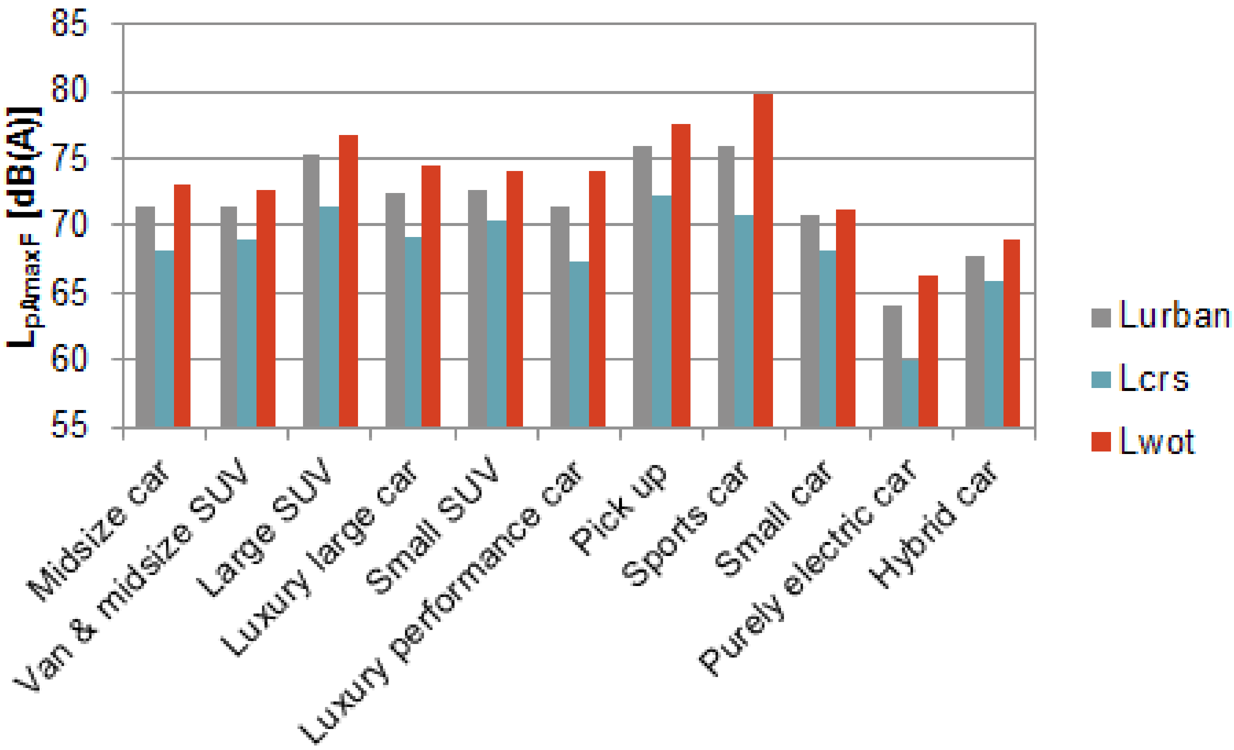

Figure 10:
Measured and collected data on noise from passenger cars. Data from pass-by measurements at a distance of 7.5 m from the road and 1.2 m above the ground. Lcrs is the noise from the cars driven at 50 km/h, Lwot is the noise from the cars accelerating from 50 km/h and Lurban is the average of these two [10].

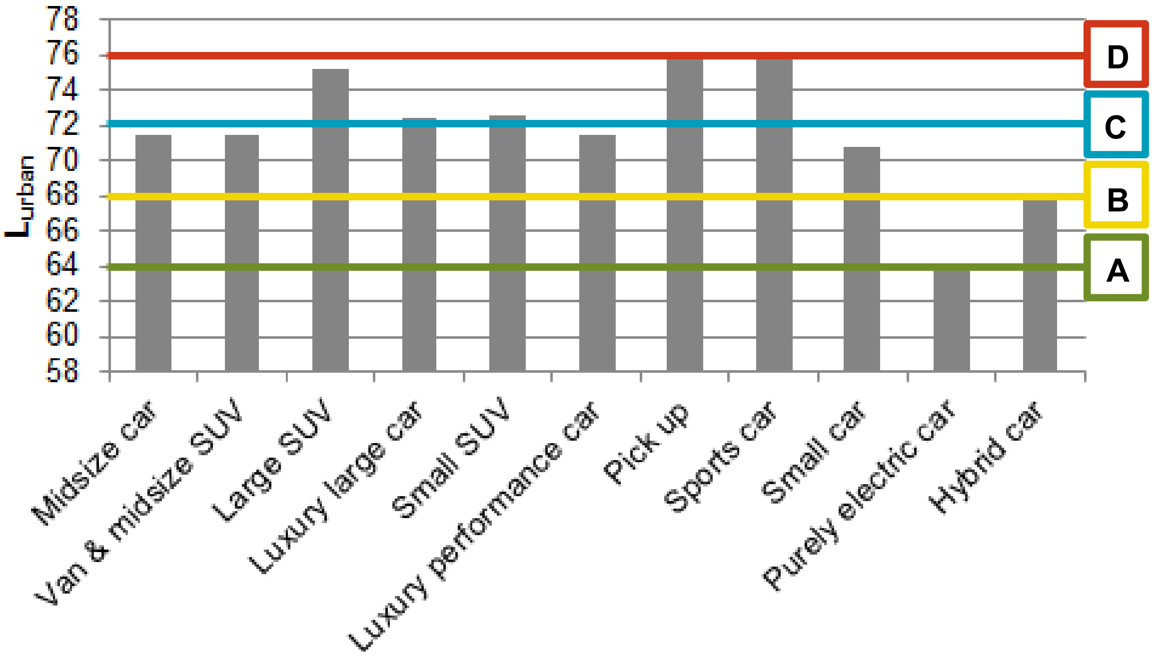

Figure 11:
The proposed noise classifications from the CityHush project based on measurements and collected data of the L_{urban} noise level, which is the average of the noise level from the cars driven constantly at 50 km/h and accelerating from 50 km/h [10].

to describe the driving conditions in urban areas. As Table 4 shows that the electric cars used for the measurements were quite small, it would seem correct to use the small ICE car for comparison. When comparing the noise levels from the electric car and the small car it can be seen that there is a difference of 7.5 dB at constant speed, 5 dB at full acceleration and 7 dB when the comparing the Lurban levels. The Lurban levels are then used for the noise classification of areas, where the noise level from the electric cars is used as the limit for the best noise class, see Figure 11.

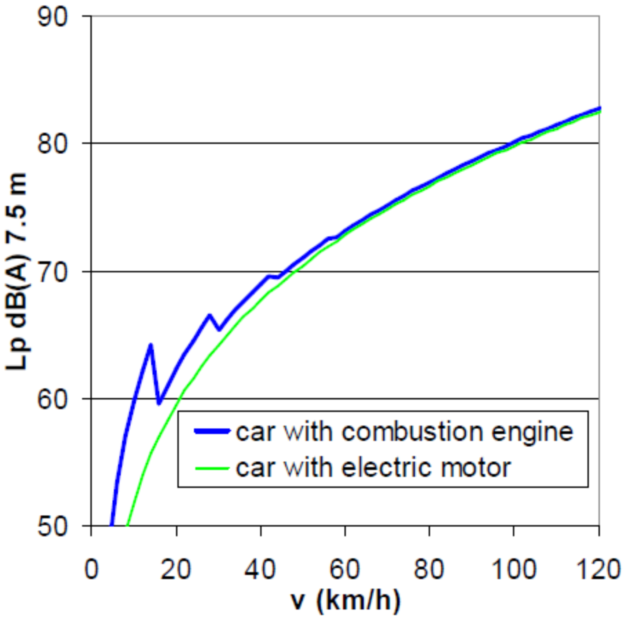

Figure 12:
The noise from an electric car and an ICE car as a function of speed measured 7.5 m from the cars. From a study by Erik de Graaff and Gijsjan von Blokland [11]. Presented here with kind permission from Gijsjan von Blokland.

The Dutch consulting engineering company M+P has shown an interest in promoting the use of low noise vehicles [11]. In connection with this, they performed some measurements of the noise from electric vehicles and ICE vehicles for comparison. Both the noise from unspecified passenger cars and from unspecified trucks was measured. The results for the noise from the trucks are presented in Section 7.2. The results for the passenger cars measured at a distance of 7.5 m can be seen in Figure 12. The difference in sound pressure level is up to around 7 dB at low speeds. Above 40 km/h there is hardly any difference and above 60 km/h there is no difference at all.

A reference which measured the propulsion noise alone was also found. In the Netherlands in 2012 investigations were made into the noise from a hybrid car and an ICE car in order to predict what effect it would have on the noise level in a city if the ICE vehicle fleet was replaced by electric or hybrid vehicles [12]. Measurements of the propulsion noise under the bonnet of two cars were taken while the cars were driven in an urban area. The tyre road surface noise was excluded in these measurements. The cars which were used were a hybrid Toyota

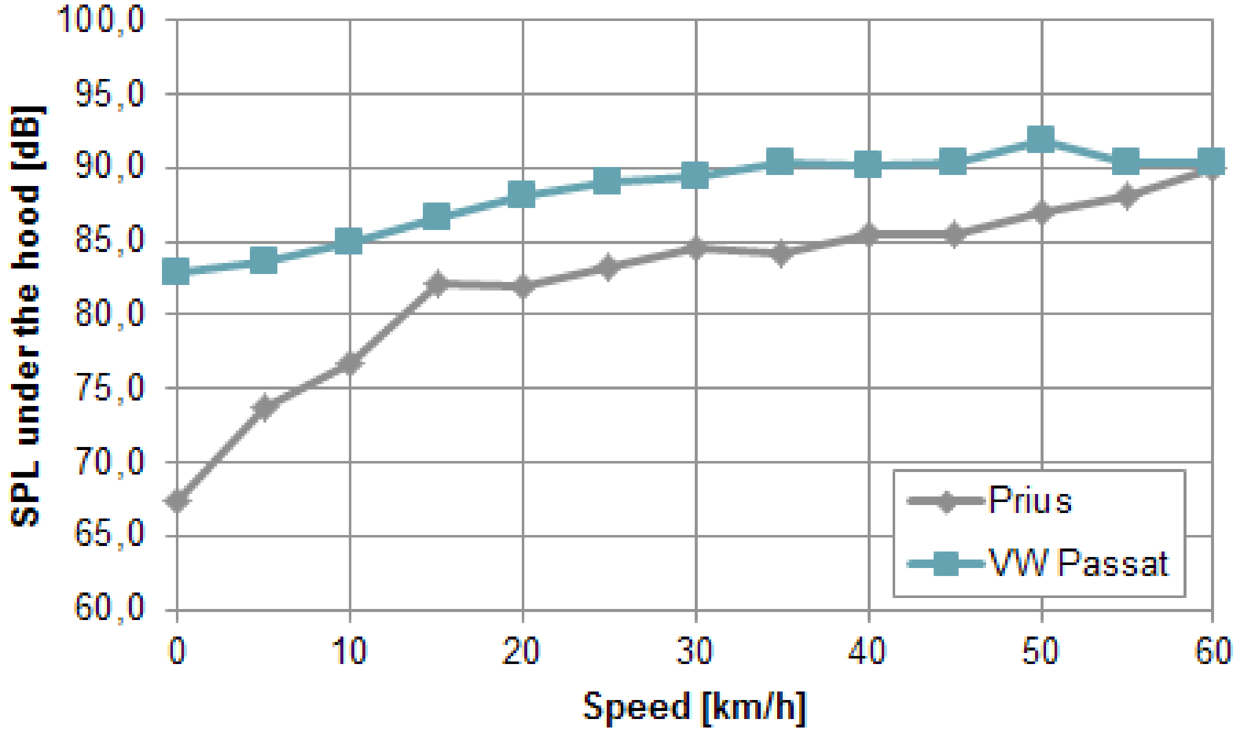

Figure 13:
Propulsion noise measured under the hood of two cars driving in an urban area in the Netherlands. The cars drove different routes of about 50 km. For both cars the average speed was 22 km/h. From a Dutch study [12].

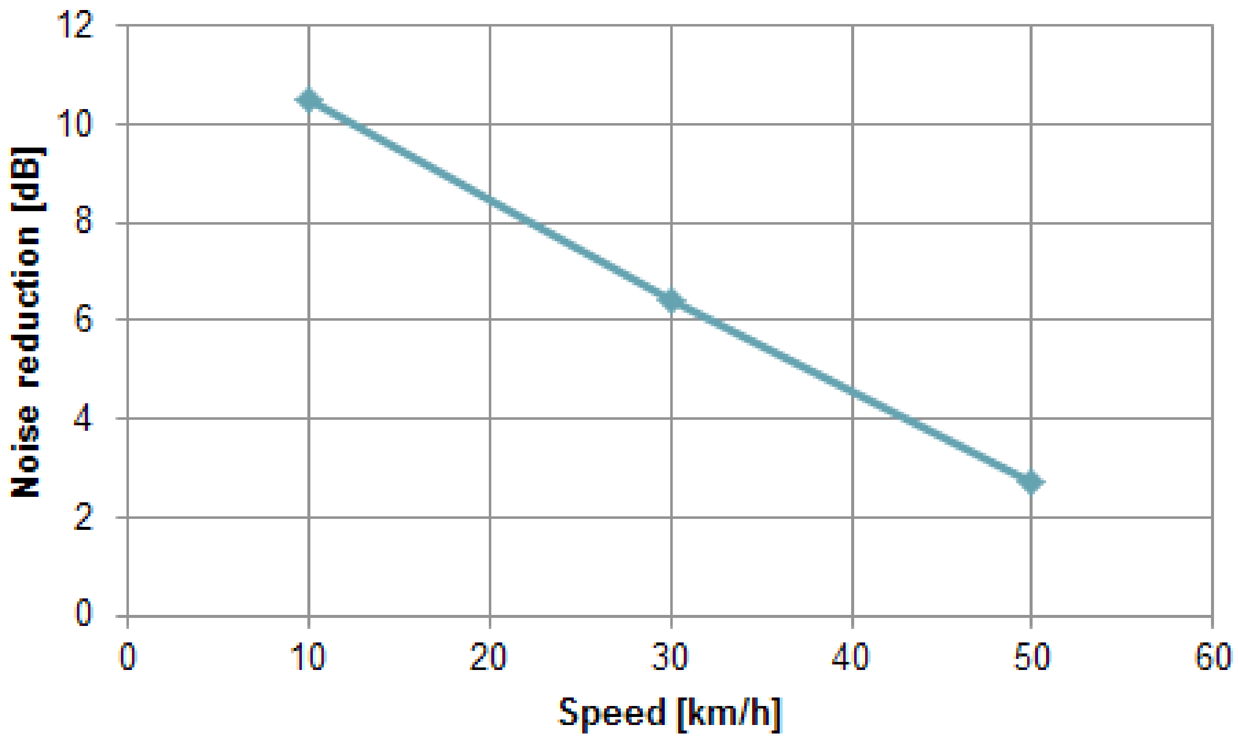

Figure 14:
Difference in total A-weighted noise from an electric car (Th!nk City) and a diesel car (VW Polo). Measured with pass-by measurements at a distance of 3 m and 1.5 m above the ground. Averaged over 5 drive bys per speed. [12].

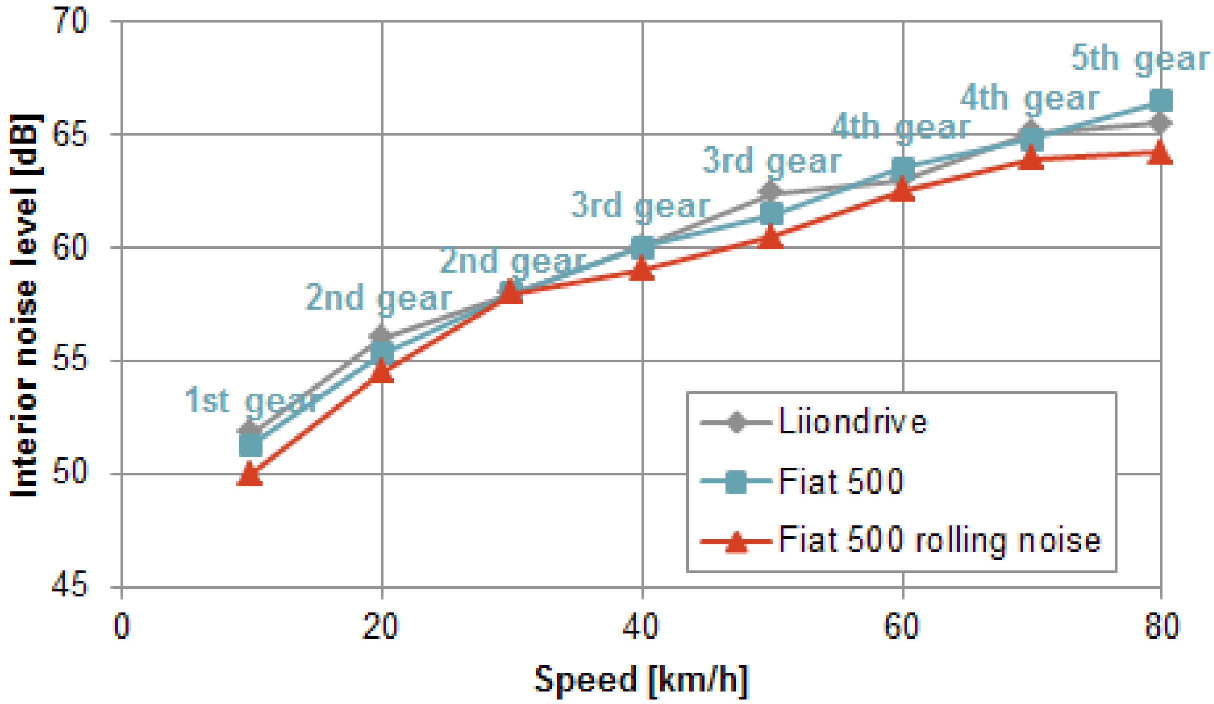

Figure 15:
Interior noise level in an electric car (Liiondrive) and a similar ICE car (Fiat 500). The Liiondrive is an electrified version of the Fiat 500 and is fixed in 2nd gear. The rolling noise of the two cars is assumed to be the same and the presented rolling noise is therefore for both vehicles. From [13].

Prius and an ICE VW Passat. The Prius switches from electric to ICE mode at around 20 km/h. The results can be seen in Figure 13, which shows that the Prius is more silent at all speeds below 60 km/h. At 5 km/h where it is assumed that the Prius was driven in electric mode the noise from the propulsion of the Prius is 10 dB lower than the noise from the propulsion of the VW Passat. At higher speeds the difference diminishes, but at 40 km/h for instance there is still a difference of around 5 dB, which indicates that the ICE of the Prius is quieter than that of the VW Passat in terms of the propulsion noise component.

The same study mentioned above [12] has also performed some pass-by measurements of noise from a small electric car (Th!nk City) and a slightly larger diesel car (VW Polo). The microphone was placed 3 m from the centre of the cars and 1.5 m above the ground. The road surface type was dense asphalt concrete (AC). The results from these measurements are presented as noise reduction as a function of speed, see Figure 14. The results predict a fairly large noise reduction, but reference [12] comments that the ICE car was slightly larger than the electric car, which could have had an influence on the difference in noise.

In 2011, a study was performed which looked at both the interior and exterior noise from an electric vehicle [13]. In this study the noise from a standard petrol Fiat 500 was compared to an electrified version of the same car. The electric version was called Liiondrive. The interior noise levels at different speeds can be seen in Figure 15. The rolling noise was also measured with the engine switched off and, since everything except for the propulsion was identical about the cars, it can be assumed that the rolling noise is the same for both. From the figure it can be seen that the difference between the electric and the ICE version of the Fiat 500 is very small and there is no clear tendency towards one being the noisier than the other. The rolling noise seems also to dominate at all speeds. As mentioned, the exterior noise level was also measured and this was carried out using pass-by measurements. The distance to the microphone is not specified. The results can be seen in Figure 16, which shows that the electric Liiondrive is not quieter than the ICE Fiat 500 at any speed and at high speeds it is even noisier. This is very unexpected. In reference [13] this is explained by the fact that the Liiondrive was fixed in 2nd gear, which could mean an increase in motor noise at high speeds.

7.2 Heavy vehicles

If a larger perspective of the impact of replacing ICE vehicles with electric vehicles on the overall sound level is taken into consideration, it would also be relevant to consider the noise from heavy vehicles such as buses and trucks.

At Aachen University in 2012, an investigation was performed on how the noise level of an electric bus reduces compared to an ICE bus [14]. The noise from 5 hybrid buses driven in both combination mode and in all electric mode together with 2 conventional buses with diesel engines was measured. Both the exterior noise

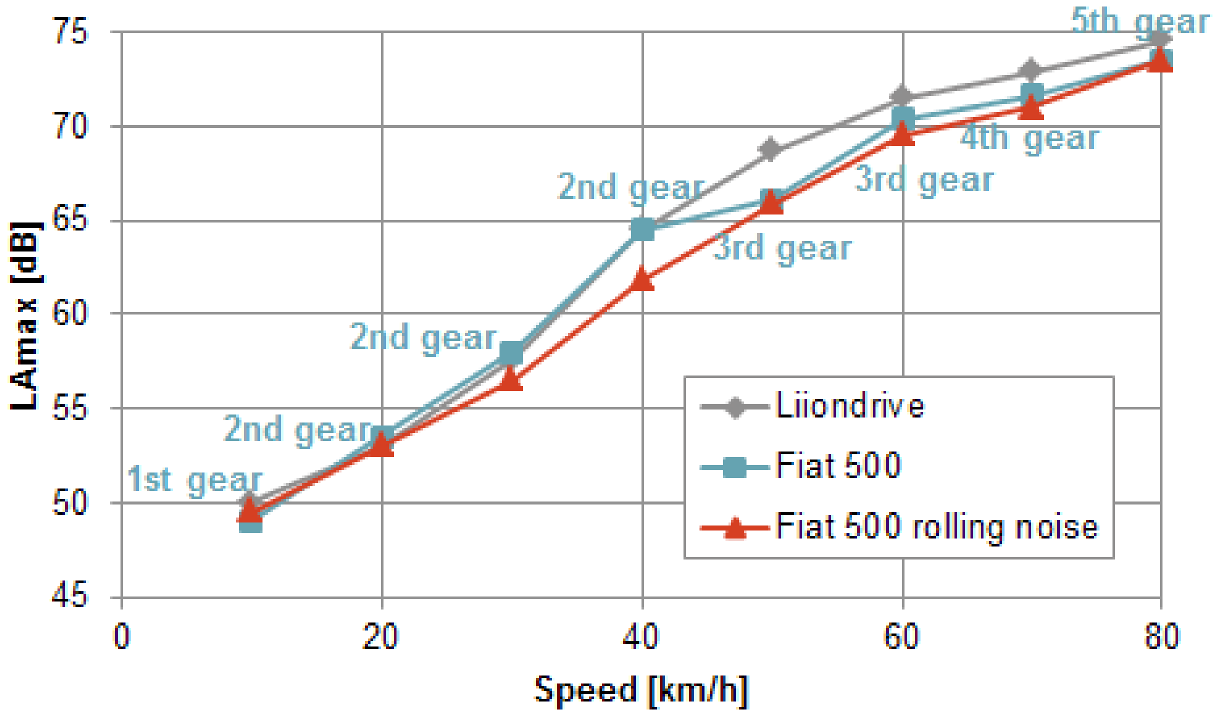

Figure 16:
Exterior pass-by noise level of an electric car (Liiondrive) and a similar ICE car (Fiat 500). The Liiondrive is an electrified version of the Fiat 500 and is fixed in 2nd gear. The rolling noise of the two cars is assumed to be the same and the presented rolling noise is therefore for both vehicles. From [13].

and the interior noise were investigated when starting and stopping the bus. The exterior noise was measured with an artificial head placed on the pavement at the side of the road where the bus stopped and started again. The exact distance to the bus and the height of the head are not stated. The speed of the bus varied from 0 to 25 km/h, which is assumed to mean that the measurement was started when the bus was driven at 25 km/h and the noise from it was then measured while it stopped at the bus stop, started again and continued until the bus reached a speed of 25 km/h again. The maximum reduction of the exterior noise from the hybrid bus driven in all electric mode was 12 dB compared to the diesel bus and the maximum reduction of interior noise was 10 dB for the hybrid driven in all electric mode. For the hybrid bus driven in combination mode the reduction of exterior noise was too small to be of any significance compared to the conventional bus. The interior noise can be reduced by up to 3 dB by using a hybrid bus driven in combination mode compared to a conventional bus.

A French study performed in 2012 looked at the noise emitted from electric and hybrid dual-axel trucks [15]. The maximum noise level from a passing truck driven at constant speed was measured 7.5 m from the centre of the track on which the truck was driving. The noise from an ICE truck was also measured for comparison. The noise levels as functions of the speed can be seen in Figure 17, which shows that there is a substantial difference between the electric truck and the ICE, especially at low speeds. At 20 km/h the difference is almost 10 dB, whereas the difference above 50 km/h is only around 1 dB.

The same study also contains measurements of the maximum A-weighted levels 4.57 m from the centre of the truck at 9 different vertical angles from 0° to 90° and at 20 km/h, 30 km/h, 40 km/h and 50 km/h. It was found that the electric truck had a lower noise level and that the sound radiation pattern was a little different, namely that the electric truck had a pronounced side radiation, see Figure 18. This is due to the fact that most of the noise came from the tyres and not from the engine.

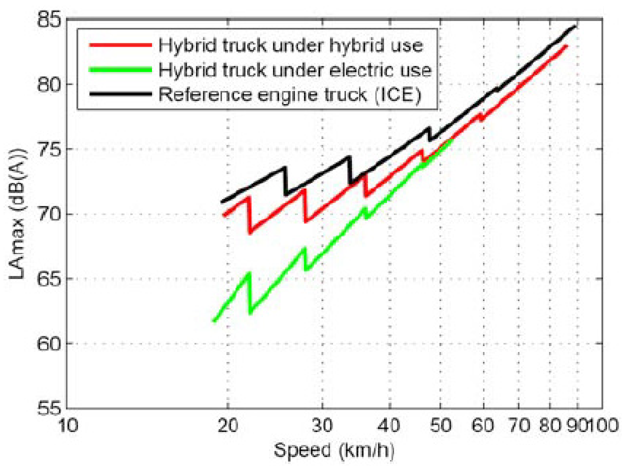

Figure 17:
The maximum A-weighted noise level from trucks driven at constant speed as a function of the speed measured 7.5 m from the trucks. From a French study by Marie-Agnès Pallas, Roger Chatagnon and Joël Lelong [15]. Presented here with kind permission from Joël Lelong.

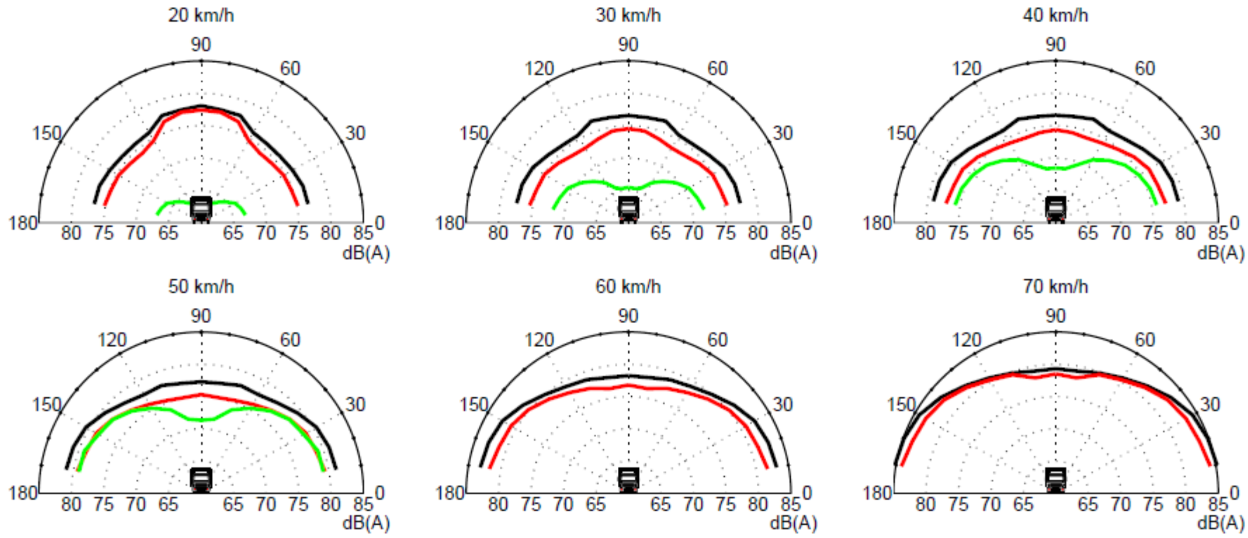

Figure 18:
The noise radiation as a function of angle from three different trucks, an electric truck (green), an ICE truck (black) and a hybrid truck (red). The driving direction of the truck is off the page and the microphone was placed 4.57 m from the centre of truck. From a French study by Marie-Agnès Pallas, Roger Chatagnon and Joël Lelong [15]. Presented here with kind permission from Joël Lelong.

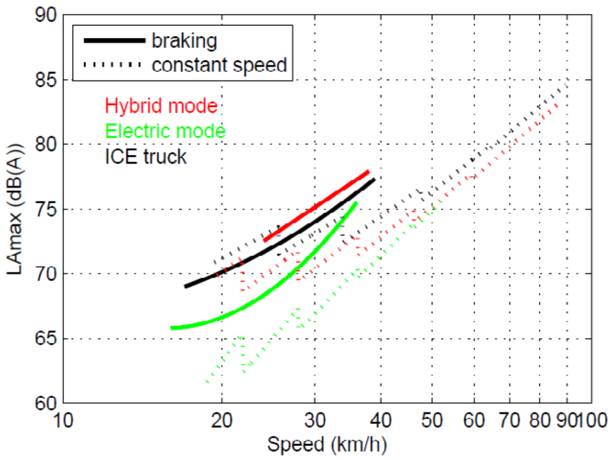

Figure 19:
The maximum A-weighted level from braking trucks measured 7.5 m from the centre of the trucks and with the braking starting at different speeds 10 m before the microphone. From a French study by Marie-Agnès Pallas, Roger Chatagnon and Joël Lelong [15]. Presented here with kind permission from Joël Lelong.

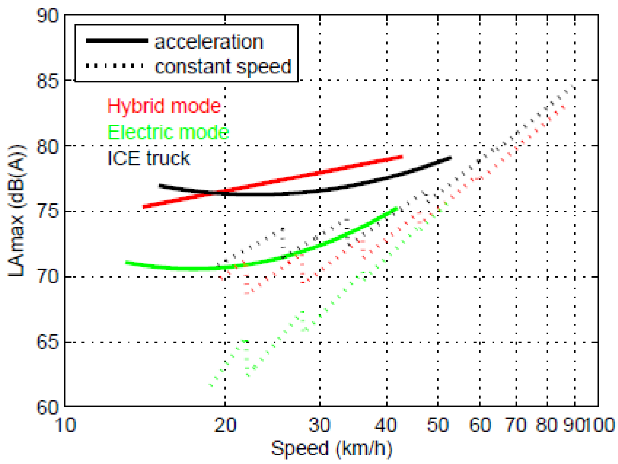

Figure 20:
The maximum A-weighted level from accelerating trucks measured 7.5 m from the centre of the trucks and with the acceleration starting at different speeds 10 m before the microphone. From a French study by Marie-Agnès Pallas, Roger Chatagnon and Joël Lelong [15]. Presented here with kind permission from Joël Lelong.

The above mentioned study [15] also investigated the noise level from the trucks on acceleration and braking. The trucks were driven at constant speed up to 10 m before the microphone and then started braking or accelerating. The measurements were taken 7.5 m from the centre of the trucks. The results are shown in Figure 19 and Figure 20, where it can be seen that the electric truck emits less noise than the ICE truck at all speeds, both when braking and accelerating. The difference is however largest at low speeds.

As mentioned, the Dutch study undertaken by the consulting engineering company M+P presented in Section 7.1 also includes trucks [11]. Figure 21 shows the noise emitted by an unspecified electric truck and an unspecified ICE truck measured at a distance of 7.5 m. The difference in sound pressure level from the ICE truck and the electric truck is up to around 15 dB at low speeds and, at high speeds of 80 km/h, there is still a difference of almost 2 dB.

7.3 Reduction of noise from electric motors

The engines of electric vehicles are often referred to as silent or quiet, and for most electric vehicles the level of the engine noise is considerably lower than that from ICE vehicles. It is therefore interesting to find out what is known about the noise from electric motors and whether

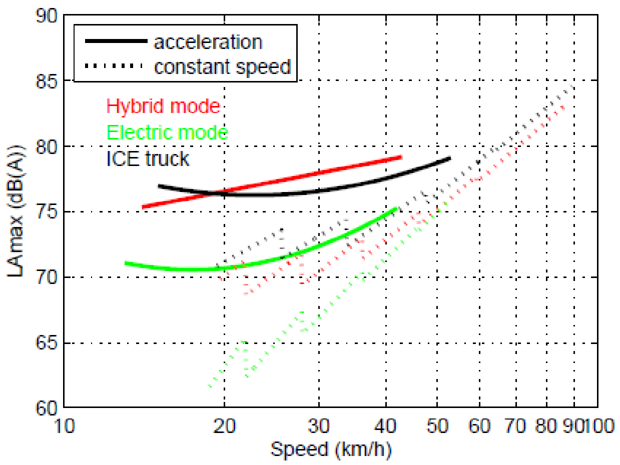

Figure 21:
The noise from an electric truck and an ICE truck as a function of constant speed measured at a distance of 7.5 m. From a study by Erik de Graaff and Gijsjan von Blokland [11]. Presented here with kind permission from Gijsjan von Blokland.

there have been any attempts to solve any noise problems.

In 2012, The Industrial Technology Research Institute in Taiwan [16] investigated the noise from the motor of an electric van and it was shown that at certain motor speeds an annoying noise with a frequency around 1.1 kHz occurred. Preliminary measurements were taken from just the motor to diagnose the noise problem. The motor was then installed in a vehicle and leaks between the cab and the motor were identified and sealed. This gave a noise reduction of 4 dB in the overall level of the interior noise. Further encapsulation was performed using a metal pan with absorbing material. This gave a 6.5 dB reduction in the exterior noise. The exterior noise was measured with pass-by measurements, but it is not specified at what distance. The speed at which these measurements were taken is not clear either, and no comments are made regarding the contribution from tyre/road noise.

A study in Aachen, Germany in 2011 [17] focused on modelling and simulating electric motors in order to investigate the noise coming from the motor and reduce any possible noise problems. This was done because audible single tones had been reported when performing test drives. A tool was developed for calculating the motor noise and it was found that it was possible to reduce the motor noise by making small changes to the shape of the magnets in the motor. It is not specified what the noise levels were before and after the changes, nor is it specified at what frequency the problem occurred. This study and the previously mentioned study show that electric motors can emit noise, and that more knowledge about the subject is needed, so that noise can be taken into consideration when designing electric vehicles.

7.4 The frequency content of noise from electric vehicles

Different types of noise sound different and two types of noise can have the same noise level, but be perceived differently. This difference is mainly due to a difference in frequency content. As combustion engines and electric motors function in different ways, it is expected that the frequency contents of the noises from the two types of propulsion will be different. It has been reported that some electric vehicles emit single tones. Single tones tend to be perceived as more annoying by people than noise with many different frequencies. It is therefore interesting to look at the frequency content of the noise from electric vehicles.

The previously mentioned Austrian study from 2009 [8], where noise from 20 different ICE vehicles passing by at the same time was compared with the noise from 20 electric vehicles, also includes the frequency spectrums of the measured noise. Figure 22 shows the frequency

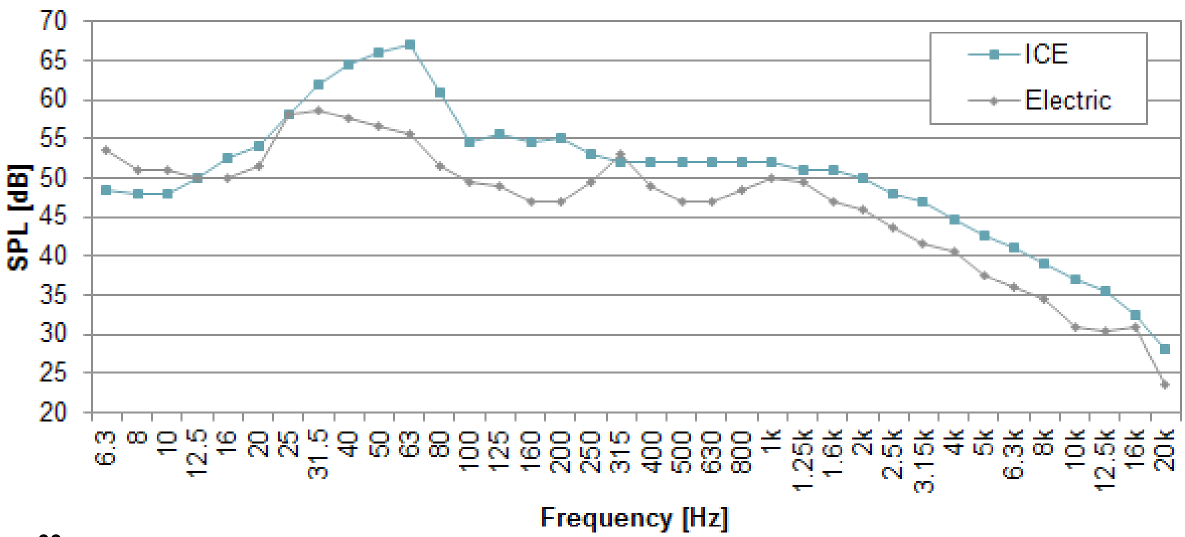

Figure 22:
The linear sound pressure level as a function of frequency for both ICE cars and electric cars driving at a constant speed of 30 km/h [8].

spectrum of the noise from the cars driven at 30 km/h and Figure 23 shows the unweighted frequency spectrum of the noise from the cars driven at 50 km/h. It can be seen in both figures that the noises from the ICE cars have very clear peaks at low frequencies (respectively at 63 Hz for 30 km/h and 50 Hz for 50 km/h), whereas the noises from the electric cars have much smaller peaks at low frequencies and sharp peaks at higher frequencies (respectively at 315 Hz for 30 km/h and 1000 Hz for 50 km/h). The peaks at higher frequencies for the noise from the electric car can cause a problem since they are easier for humans to hear. In reference [8] the peaks were reported as being heard as "singing" noises, which can cause annoyance. Figure 24 shows the frequency spectrum for the stop-and-go situations and it can be seen that the shape of the spectrums are very similar, although the levels differ greatly.

The previously mentioned Japanese study from 2012 [4] concerning the noise from approaching electric vehicles also includes investigations of the frequency spectrums of the noise from these vehicles. The noise from electric cars was measured both with and without artificially added noise. The artificial noise was created following the Japanese guidelines from 2011 that recommend sounds which simulate the sound of ICE vehicles. The results can be seen in Figure 25, Figure 26, Figure 27 and Figure 28. Figure 25 contains the A-weighted frequency spectrums for the noise from the cars driven at 10 km/h, Figure 26 contains the A-weighted frequency spectrums for the noise from the cars driven at 10 km/h with added noise, Figure 27 contains the A-weighted frequency spectrums for the noise from the cars driven at 20 km/h and Figure 28 contains the A-weighted frequency spectrums for the noise from the cars driven at 20 km/h with added noise. It is apparent that the frequency spectrums for the ICE cars and the electric cars without added noise differ more when driven at 10 km/h than when driven at 20 km/h. When looking at the frequency spectrums for 10 km/h, it can be seen that the

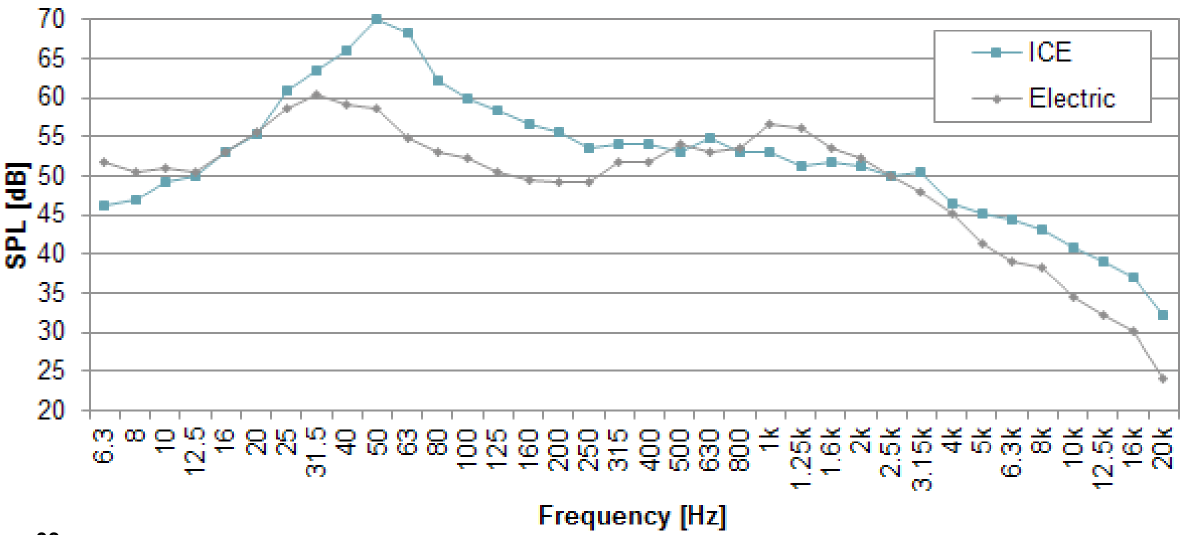

Figure 23:
The linear sound pressure level as a function of frequency for both ICE cars and electric cars driving at a constant speed of 50 km/h [8].

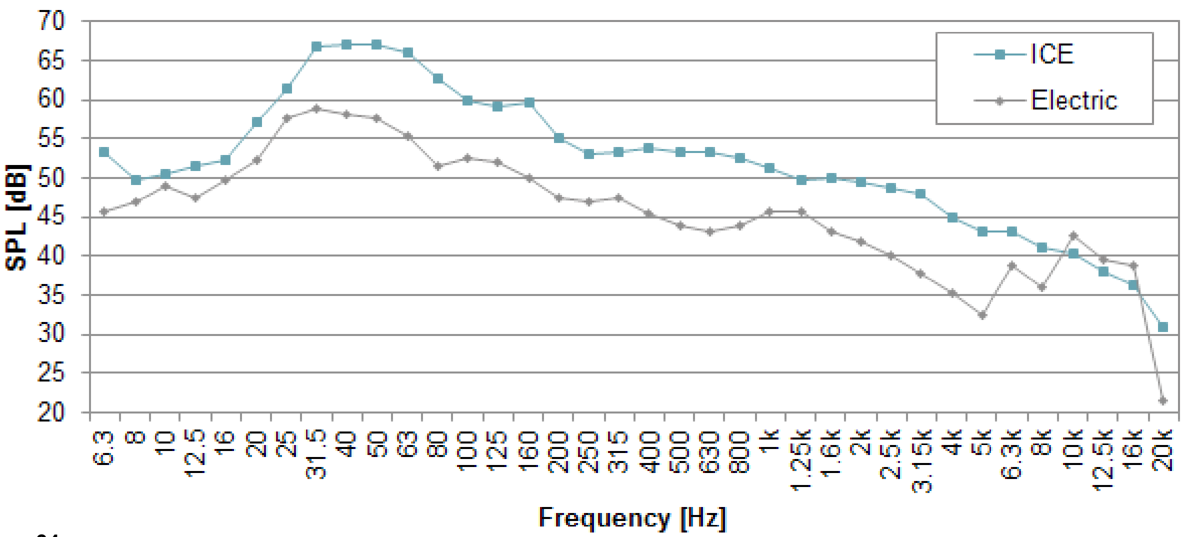

Figure 24:
The linear sound pressure level as a function of frequency for both ICE cars and electric cars in stop-and-go situations [8].

added noise seems to have most content at frequencies of around 2 kHz or 2.5 kHz. At 20 km/h the frequencies of the added noises cannot be seen as clearly, which suggests that the tyre/road noise level is higher than the added noise. The noise added to EV-2 can however still be seen at 20 km/h as a peak at 2.5 kHz, although this vehicle is also the vehicle which has the lowest noise level at 20 km/h without the added noise.

An American study [5] from 2012 which investigated noise from an electric passenger car was mentioned in Section 7.1. This study also analysed the frequency

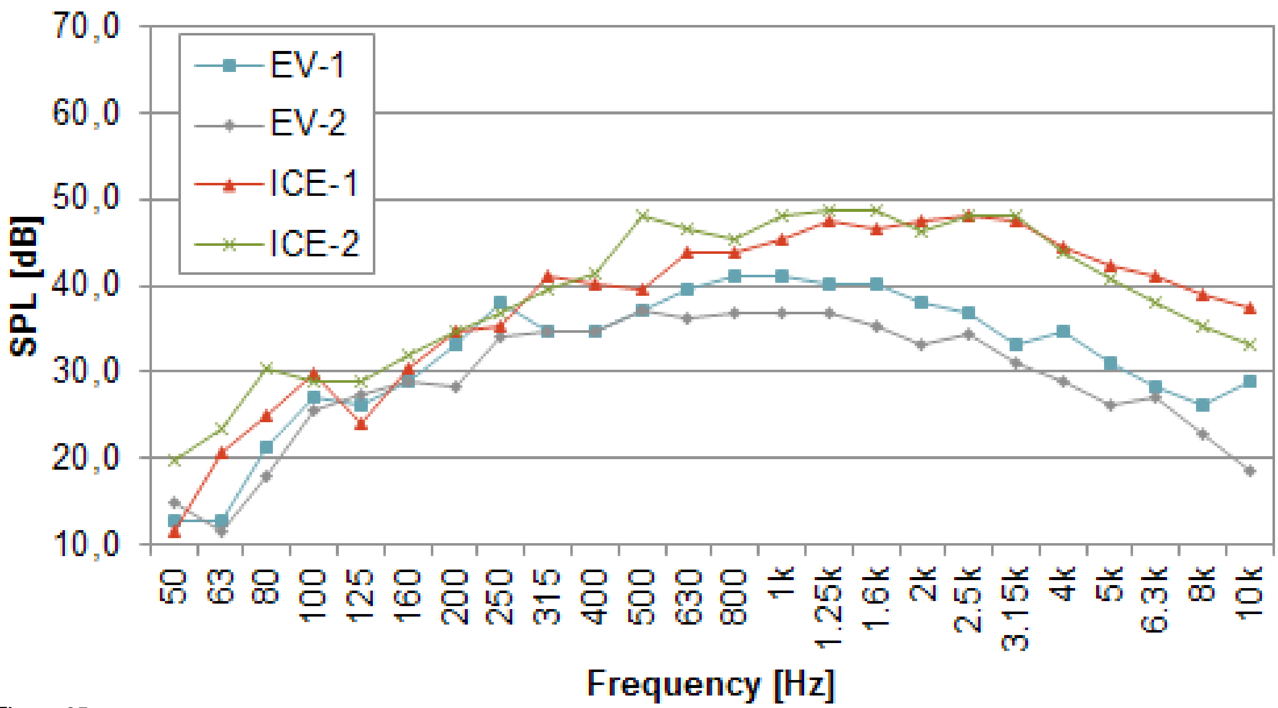

Figure 25:
The A-weighted frequency spectrums for vehicles driven at a constant speed of 10 km/h without artificial sound added to the electric vehicles [4].

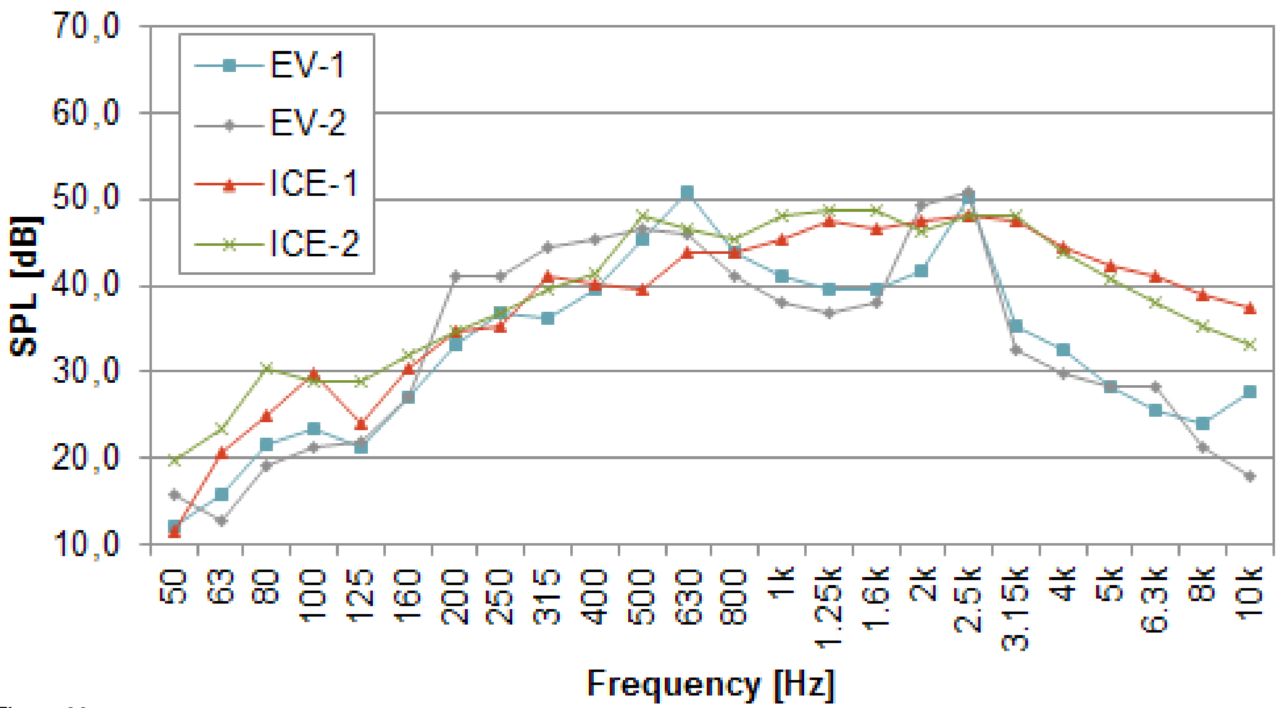

Figure 26:
The A-weighted frequency spectrums for vehicles driven at a constant speed of 10 km/h with artificial sound added to the electric vehicles [4].

content of the noise emitted from the electric car and the ICE car. The cars were driven at 5 mph (8 km/h), 30 mph (48 km/h) and 60 mph (97 km/h) both at constant speeds and on acceleration. Only the results for 5 mph and 60 mph are shown here, see Figure 29 to Figure 32, which contain the unweighted frequency spectrums.

There is a slight tendency for the frequency spectrum for the ICE car to be flatter than that for the electric car, which has more peaks, especially at low speeds. When accelerating from 5 mph the electric car has considerably less low frequency content than the ICE car, while the difference is smaller when the cars accelerate from

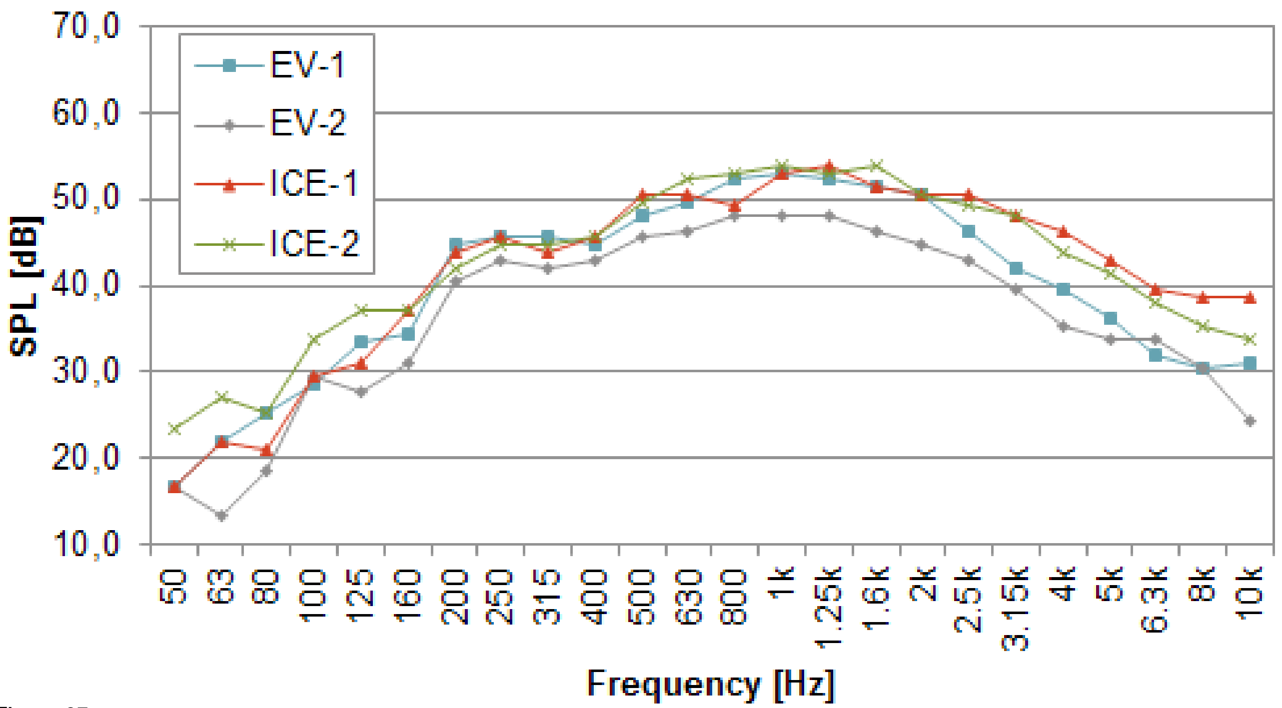

Figure 27:
The A-weighted frequency spectrums for vehicles driven at a constant speed of 20 km/h without artificial sound added to the electric vehicles [4].

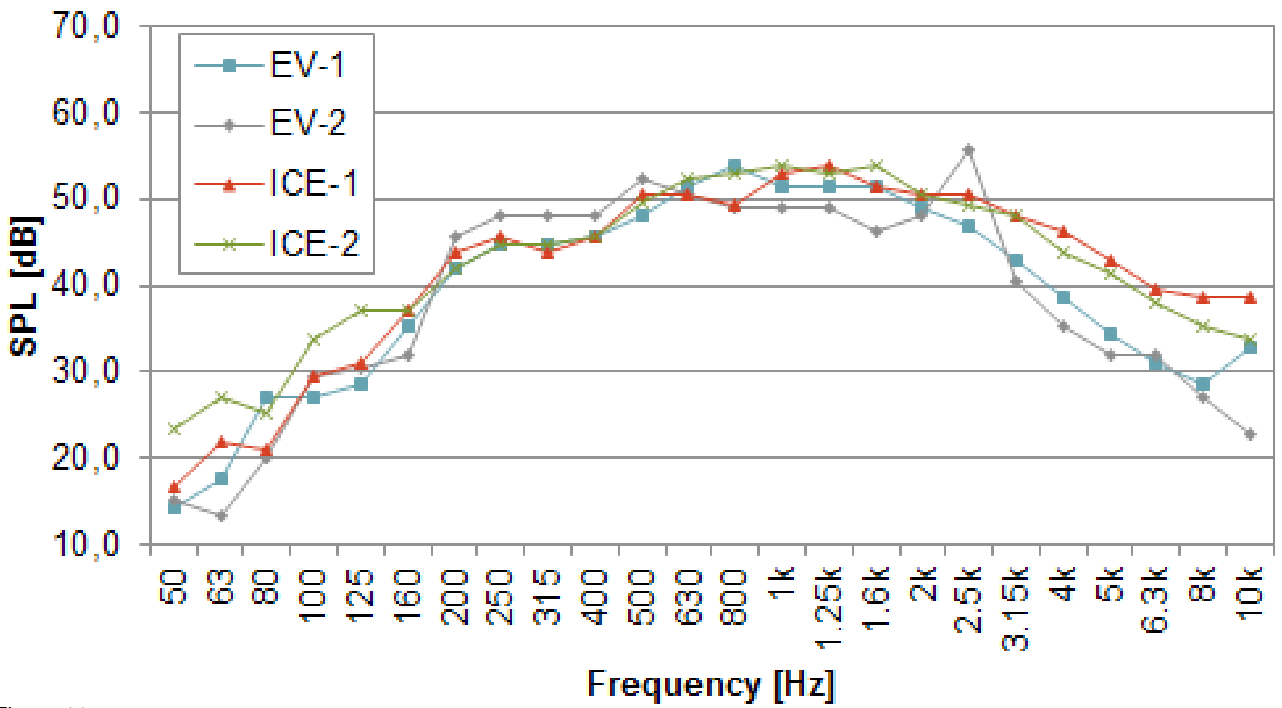

Figure 28:
The A-weighted frequency spectrums for vehicles driven at a constant speed of 20 km/h with artificial sound added to the electric vehicles [4].

60 mph. For a constant speed of 5 mph the level from the ICE car is much higher at most frequencies, while at 60 mph the difference is greatest at low frequencies. At 97 km/h there is an increase of up to 15 dB from 1000 Hz and upwards. This is presumably the tyre/road noise that starts at around 1000 Hz. This phenomenon is not seen at 8 km/h where the tyre/road noise is very low and not dominant.

The previously mentioned American study from 2010 [6] also looked at the frequency content of the noise from the hybrid cars and their ICE 'twins', with the hybrid cars

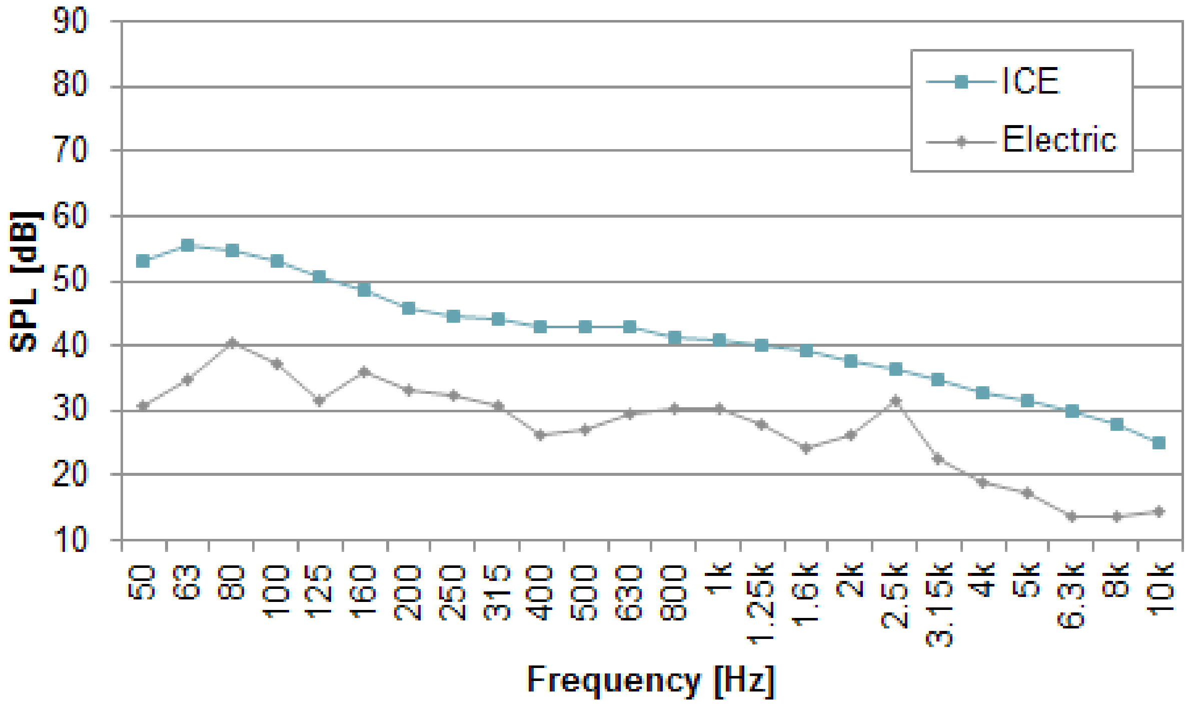

Figure 29:
Linear frequency spectrum of noise from an electric car (Volt) and an ICE car (Auto) driven at 5 mph (8 km/h) [5].

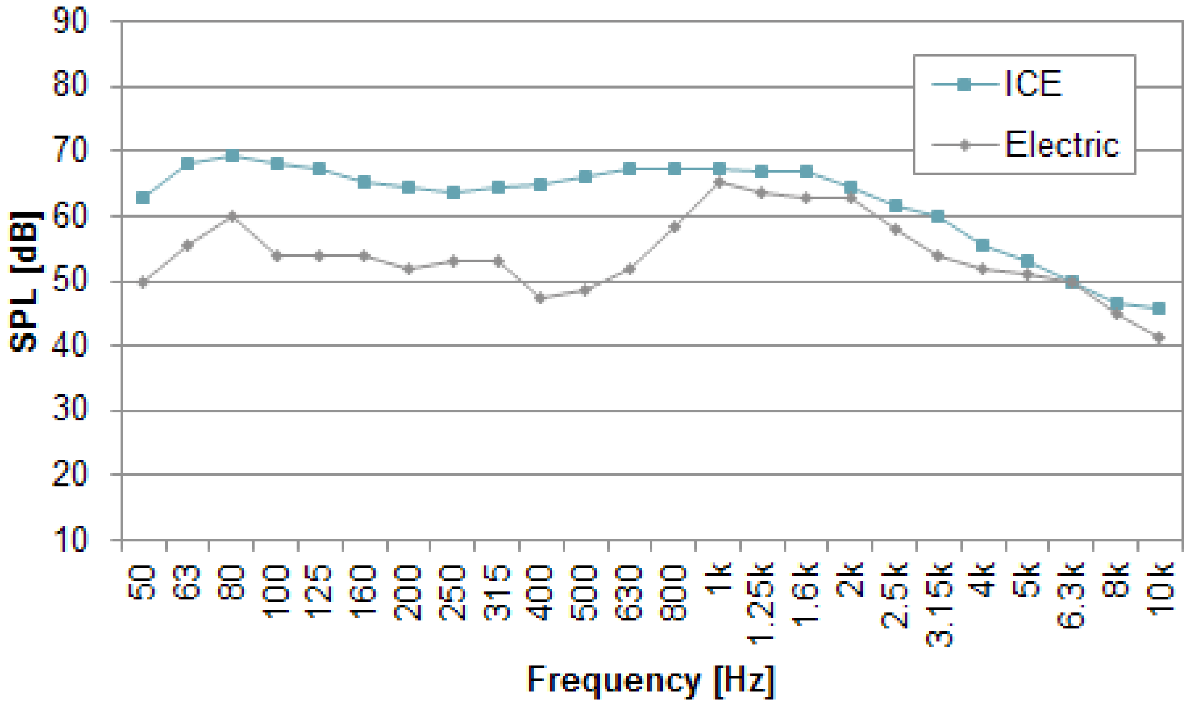

Figure 30:
Linear frequency spectrum of noise from an electric car (Volt) and an ICE car (Auto) driven at 60 mph (97 km/h) [5].

driven in electric mode. The measurements were taken 3.7 m from the centre of the track. One sample from the pass-by measurements with the cars driven at 6 mph (9.7 km/h) was used. The results of this can be seen in Figure 33 and Figure 34, which contain the unweighted frequency spectrums. There is a tendency for the two hybrid cars in electric mode to have less high frequency content. The noise from the Toyota Prius has a peak at 5 kHz, which might be perceived as an audible single tone and therefore cause annoyance. The noise from the Toyota Matrix has a peak at 80 Hz, but this is such a low frequency that this will not be heard as a single tone. Reference [6] contains more measurements of the frequency contents of the noise from the different cars at

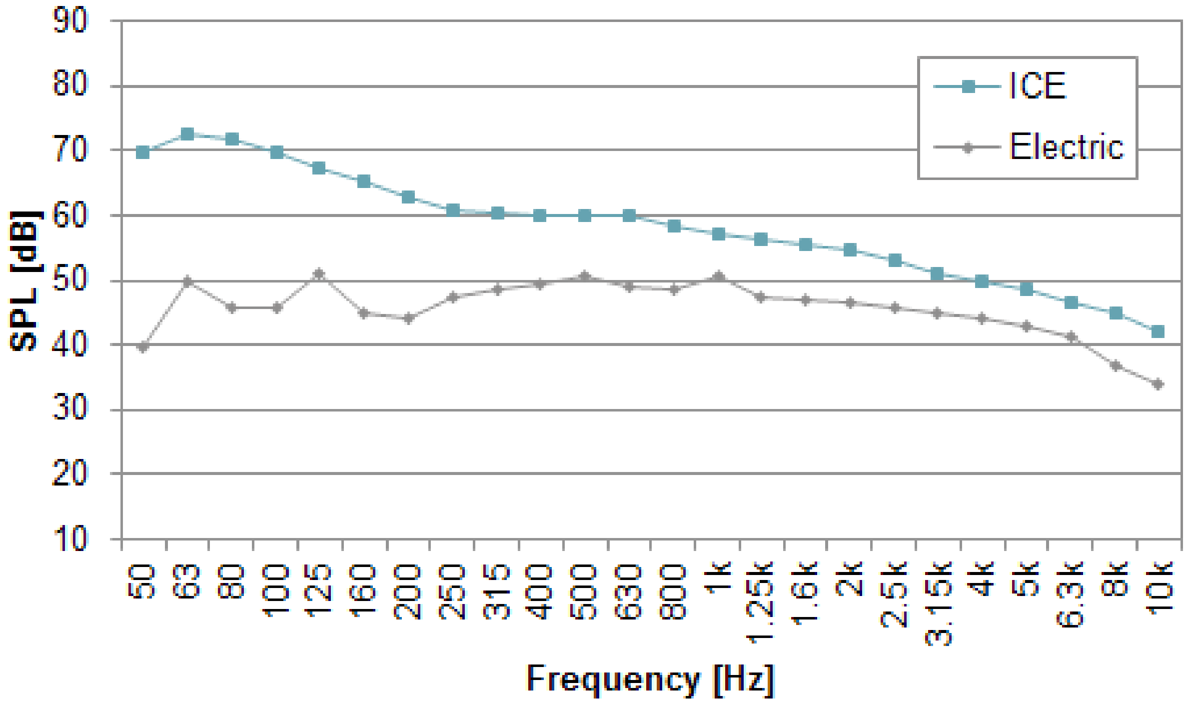

Figure 31:
Linear frequency spectrum of noise from an electric car (Volt) and an ICE car (Auto) accelerating at 5 mph (8 km/h) [5].

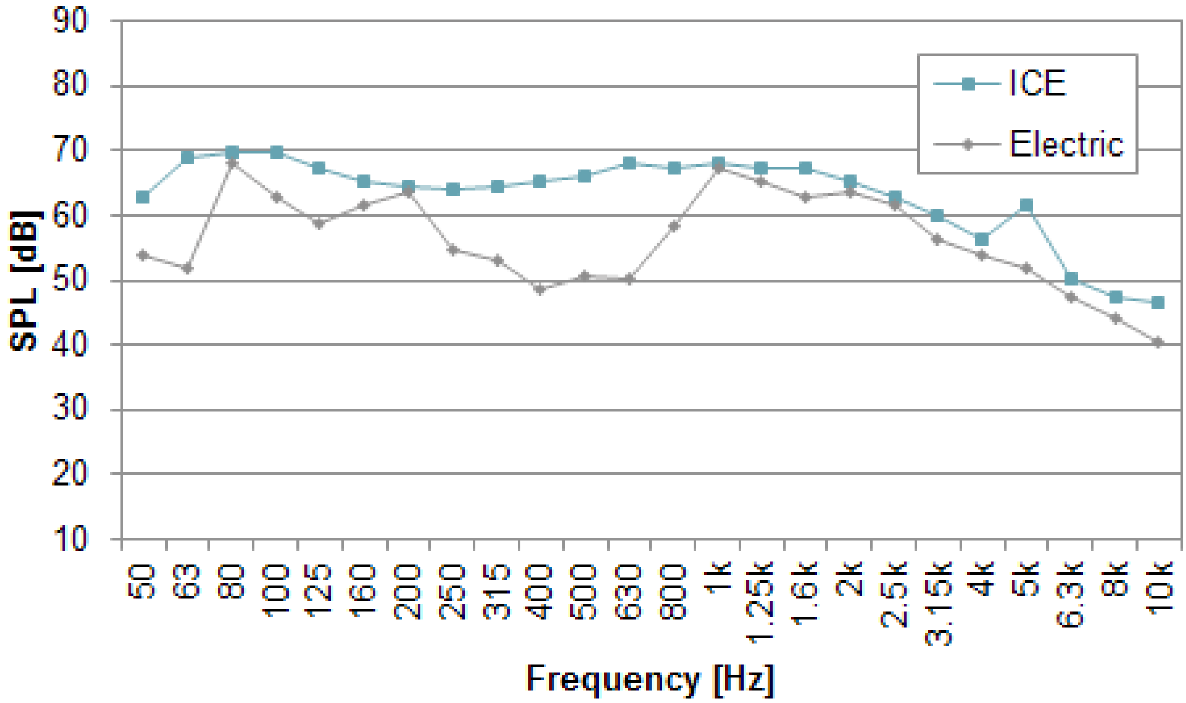

Figure 32:
Linear frequency spectrum of noise from an electric car (Volt) and an ICE car (Auto) accelerating at 60 mph (97 km/h) [5].

different speeds and in different operating conditions, i.e. deceleration, reversing and idling, although they are not included here.

The Master's thesis [7] mentioned in Section 7.1 also contains results for the frequency content of the noise from the electric vehicle and the ICE vehicle driven at 40 km/h and 70 km/h, measured with controlled pass-by, see Figure 35 and Figure 36. At 40 km/h there is a large difference at around 100-200 Hz, at middle frequencies (1 kHz to 2.5 kHz) the levels are very similar and at high frequencies the difference grows larger again, the ICE being the noisiest car at all speeds. At 70 km/h the difference at low frequencies is smaller, but the frequency

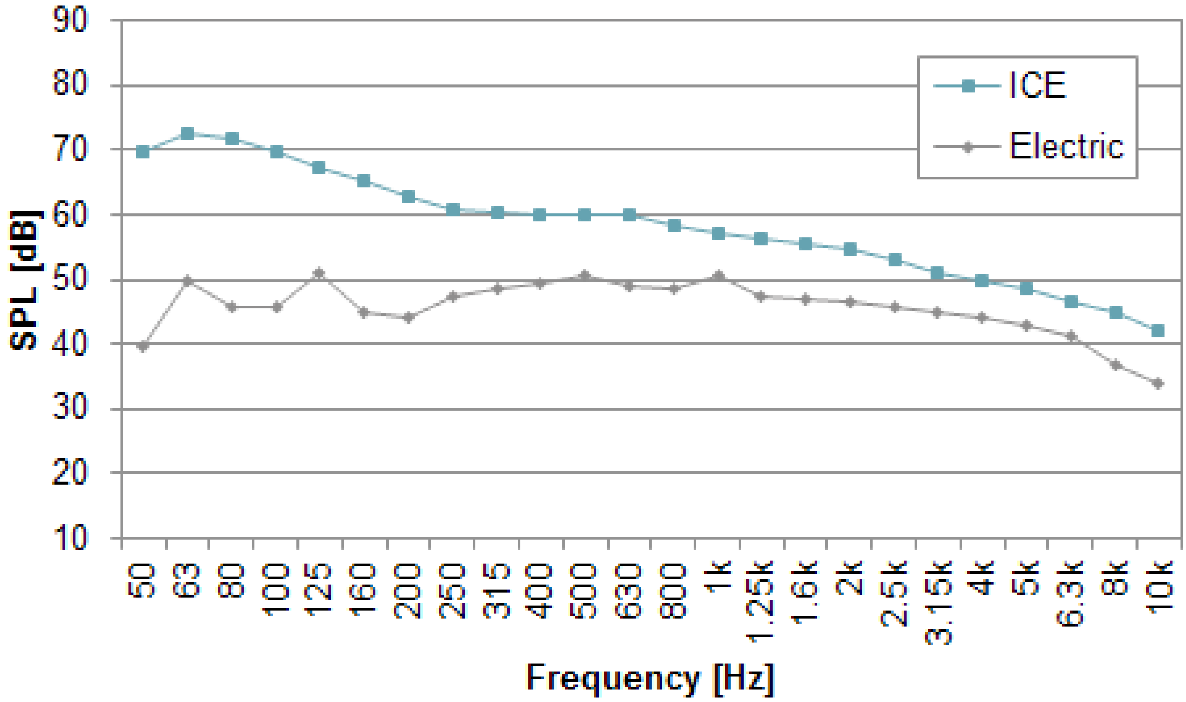

Figure 33:
The linear spectrum of noises emitted from a Toyota Prius (hybrid driven in electric mode) and a Toyota Matrix (ICE) when driven at 6 mph [6].

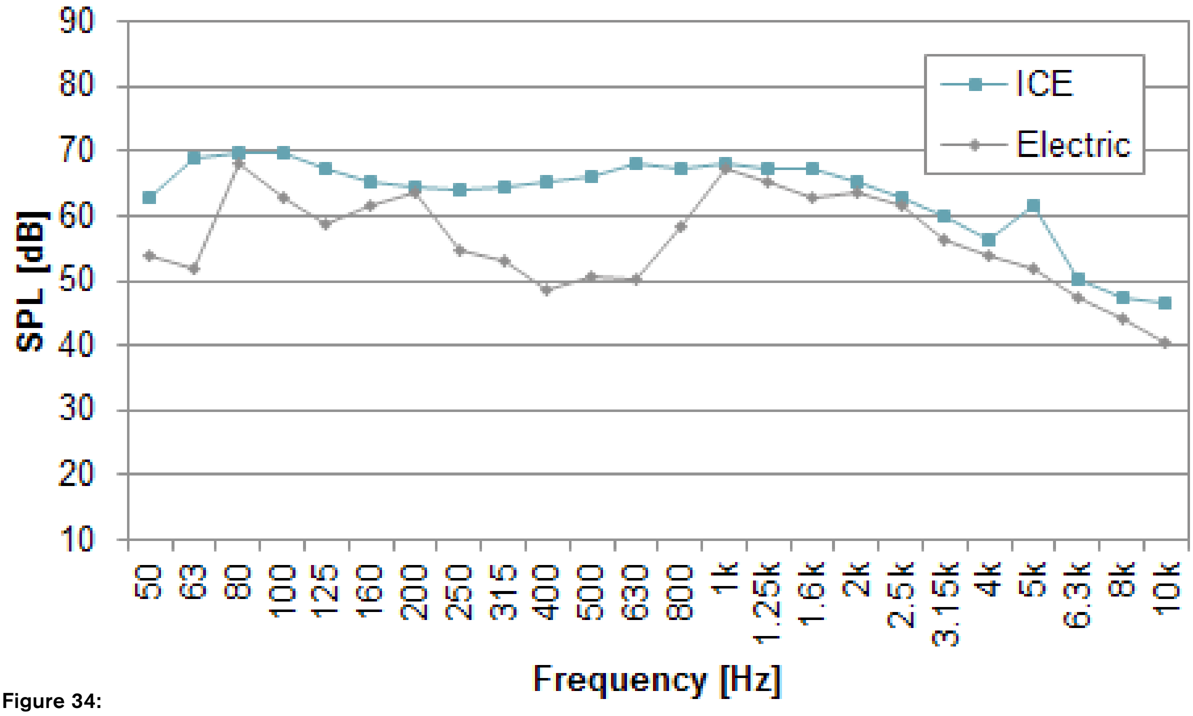

Figure 34:
The linear spectrum of noises emitted from a Hybrid Toyota Highlander (driven in electric mode) and an ICE Toyota Highlander when driven at 6 mph [6].

content of the noise from the ICE car still differs most at high and low frequencies and less at middle frequencies from the frequency content of the noise from the electric car.

The CityHush project [10] also included frequency analyses of the noise from small electric passenger cars. Figure 37 and Figure 38 show examples of the spectrums from two of the cars at 10 km/h and 55 km/h. Figure 37 contains the spectrums of the noise from a Fiat 500 and Figure 38 contains the spectrums of the noise from a Citroën C-zero. More spectrums can be seen in the reference, but only two cars driven at two different speeds are shown here as all spectrums looked rather

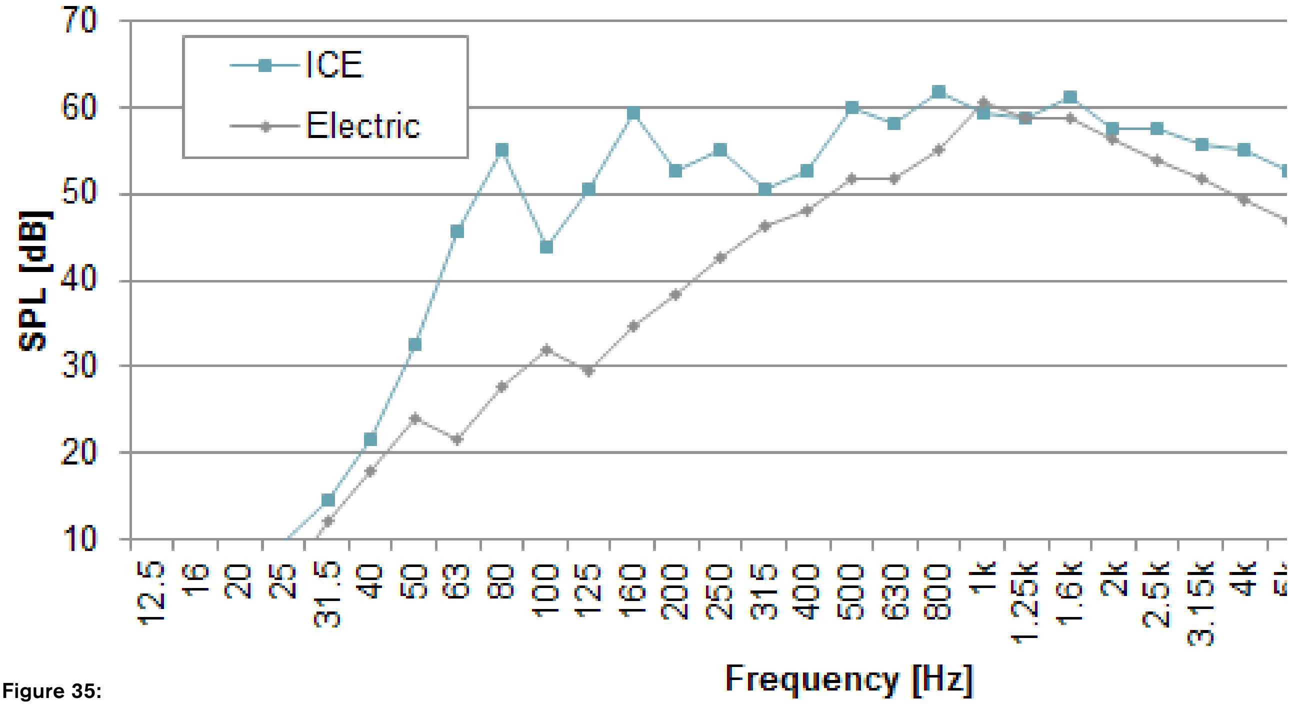

Figure 35:
The A-weighted frequency contents of the noise from cars driven at a constant speed of 40 km/h measured 7.5 m from the centre of the cars and at a height of 1.2 m. From a Danish Master's thesis. [7].

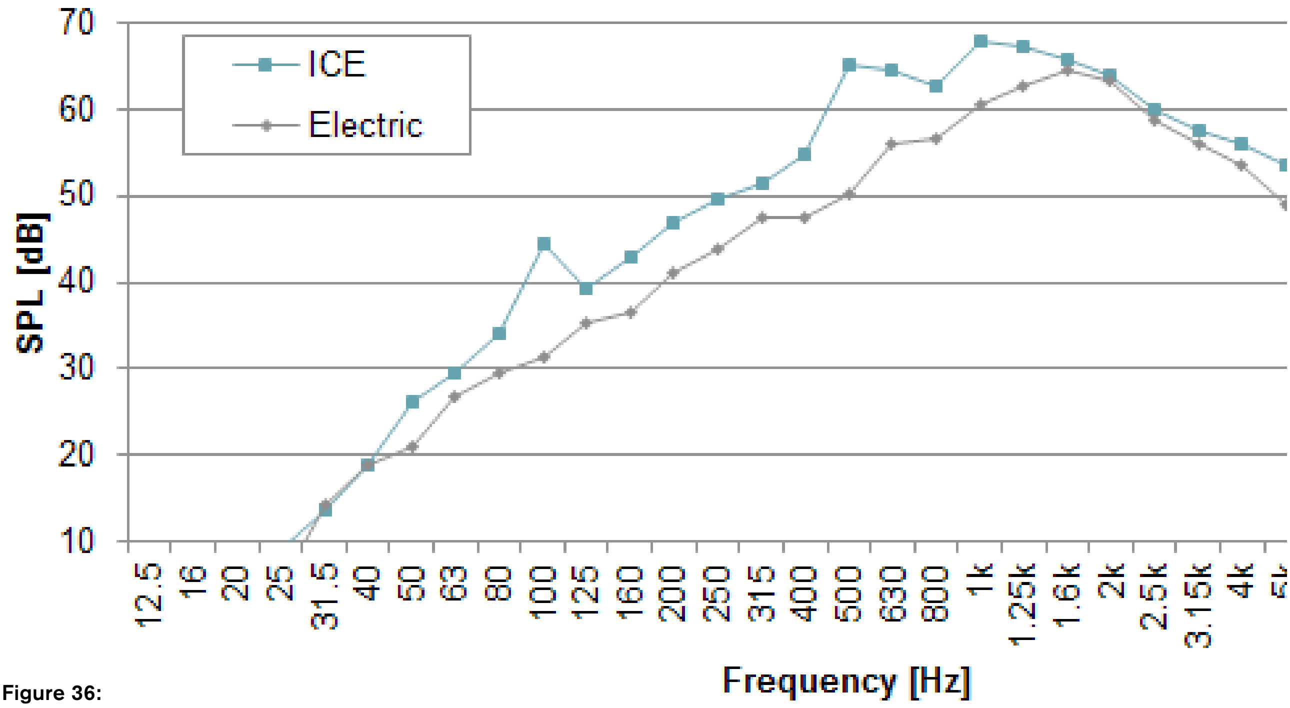

Figure 36:
The A-weighted frequency contents of the noise from cars driven at a constant speed of 70 km/h measured 7.5 m from the centre of the cars and at a height of 1.2 m. From a Danish Master's thesis [7].

similar. The noise from all electric cars driven at 10 km/h had a more or less pronounced peak at 250 Hz. In the examples shown here, Figure 37 shows a small peak, while Figure 38 shows a very clear peak. At 50 km/h the noises mostly contain middle frequencies. No spectrums of the noise from ICE cars were presented in reference [10].

7.5 Subjective perceptions of noise from electric vehicles

This literature survey focuses on objective measurements of the noise emitted from electric vehicles, although a couple of references were found where perceptions of the noise emitted from electric vehicles were investigated.

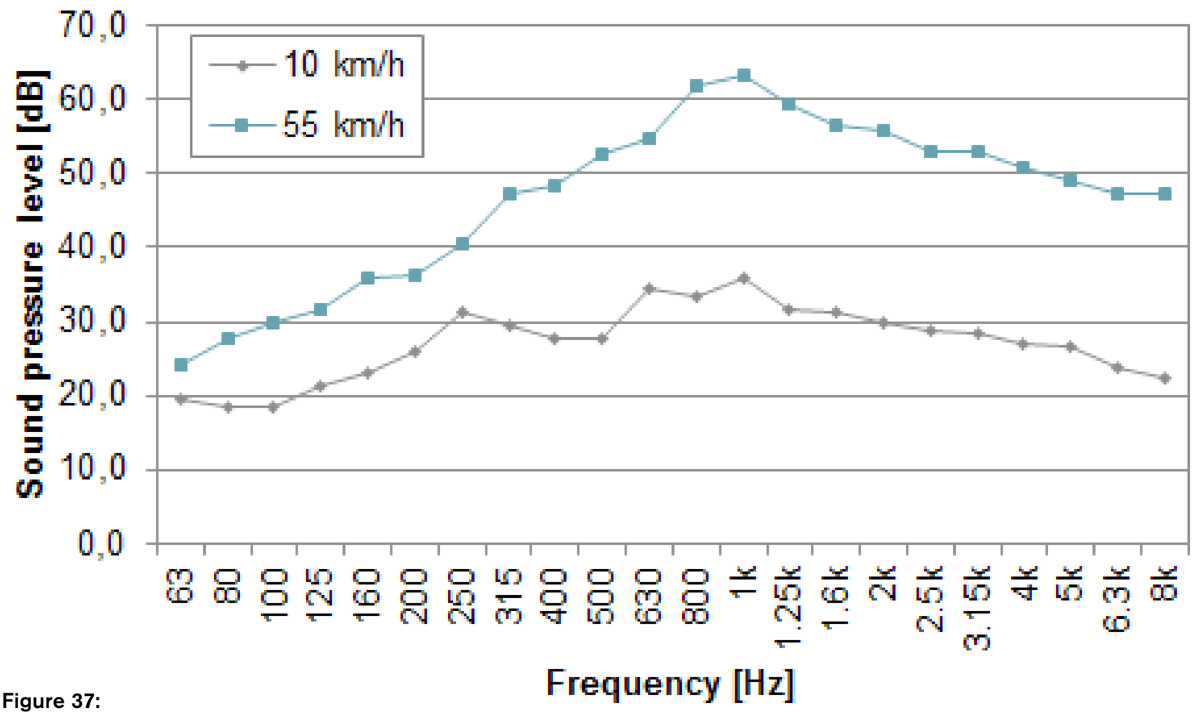

Figure 37:
A-weighted frequency spectrum for the Fiat 500 at constant speeds from the CityHush project measured with pass-by at a distance of 7.5 m and 1.2 m above the ground [10].

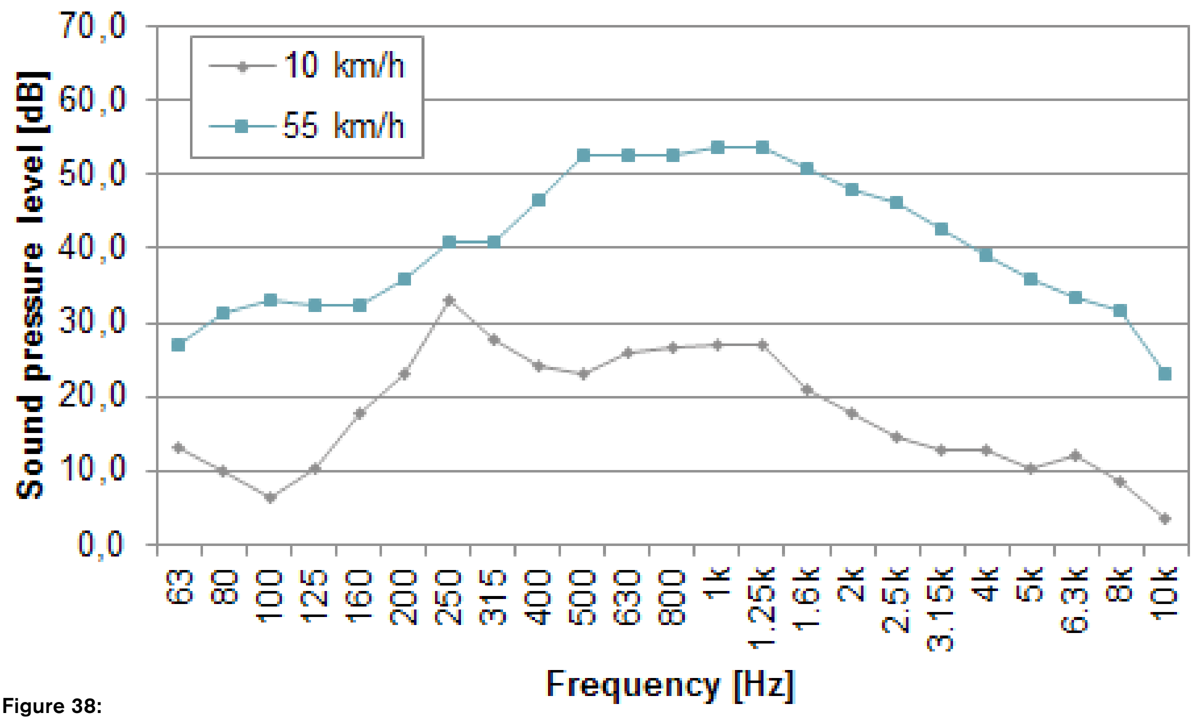

Figure 38:
A-weighted frequency spectrum for the Citroën C-zero at constant speeds from the CityHush project measured with pass-by at a distance of 7.5 m and 1.2 m above the ground [10].

A study of the noise emitted from hybrid buses from 2012 [14] was mentioned in Section 7.2 and this also included a questionnaire survey, which showed that people tend to prefer riding in electric buses. This corresponds well with the fact that the same study found that the noise in the hybrid bus was up to 10 dB lower compared to an ICE bus.

Japanese researchers carried out a questionnaire survey in 2012 [18], in which 104 people in the Fukuoka city area in Japan and 27 people in the Munich city area in Germany answered a questionnaire about their experiences of noise from electric and hybrid vehicles. Out of these people, 48 of the Japanese respondents and 16 of the German respondents answered yes to having listened to a hybrid or electric vehicle travelling slowly. Out of these, 91.2% of the Japanese and 87.5% answered that they found the sound “quiet” or “very quiet”. The study also investigated the respondents’ opinions about the need to add sound to electric and hybrid vehicles to lower the risk to pedestrians. It was found that 60% of the Japanese respondents and 78% of the German respondents thought it was necessary to add artificial sound. This study therefore also indicates that hybrid and electric vehicles are considered to be quiet and in some cases even too quiet.

The German study of the noise emitted from ICE cars and comparable electric cars [9] which was mentioned in Section 7.1 also studied subjective opinions about the noise from two of the cars. The cars were the ICE car, the Opel Agila, and the comparable electric car, the Stromos. The test subjects stood on the side of a street and the cars then passed by one at a time at a constant speed of 30 km/h. The test subjects then crossed the street after the car had passed and answered a questionnaire. There were 240 participants and their age ranged from 5 to 95 years old. 14% of them were mildly, moderately or severely hearing impaired, of which 70% did not use a hearing aid and 15% were visually impaired. The results of the questionnaire can be seen in Figure 39, which shows that the difference between the descriptions of the noise from the cars is very small. The only point where there is an apparent difference is the loudness and even this difference is very small. It should be noted that the two cars which were chosen for subjective comparison were those which emitted sound levels closest to each other. The Agila had a sound level of 59 dB at 30 km/h measured 7.5 m from the track and the Stromos had a sound level of 57 dB.

The reference mentioned in Section 7.1 concerning the noise from an electrified Fiat 500 [13] also contained some subjective results. These subjective tests were carried out from the driver’s perspective. The noise was rated on three criteria; pleasantness, dynamic impression and preference. The dynamic impression is an expression for how the sound in the car changes in different driving situations. Drivers prefer to be able to hear when the car is accelerating, for instance. The noise from the electric vehicle was presented to the test subjects in the original version and in versions where different parts of the frequency spectrum were attenuated. This allowed for an investigation into what parts of the frequency content are important to different subjective aspects. This showed that removing some of the high frequencies improved the pleasantness and preference ratings. Reducing the middle frequencies also improved the pleasantness but to a lesser degree and it also decreased the dynamic impression rating. Reducing the low frequencies had no significant effect. The ICE Fiat 500 was rated similar in pleasantness to the original Liiondrive noise and the dynamic impression of the ICE Fiat 500 was rated better than the Liiondrive noise. Even though the dynamic impression was rated better for the ICE Fiat 500 than for the Liiondrive the ICE noise was not preferred for the Liiondrive. This indicates that people want the car they drive in to sound like it is using the propulsion it actually is using.

7.6 Predictions about noise reduction in cities due to electric vehicles

If it is found that electric vehicles are quieter than ICE vehicles, then it would be interesting to investigate how

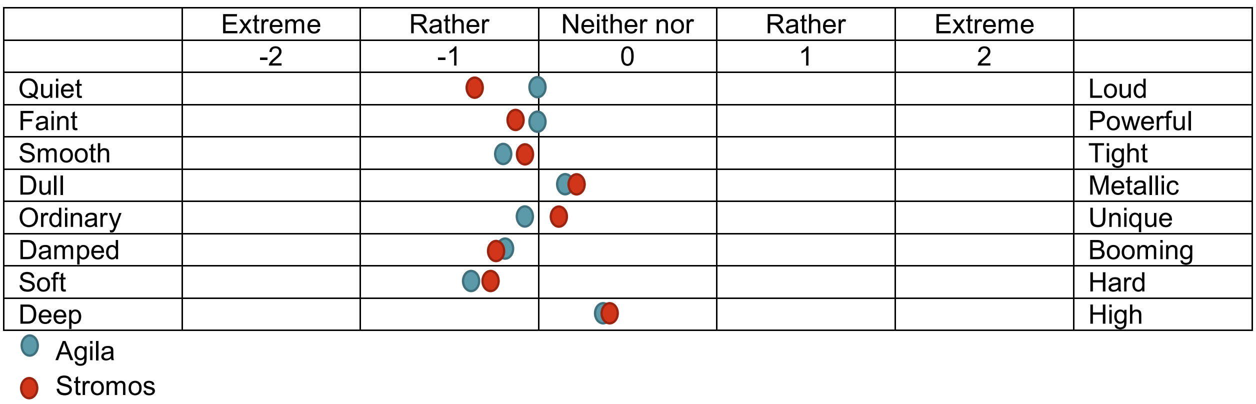

Figure 39:
The subjective evaluation of the noise from the electric Stromos and the ICE Agila. From a German study [9].

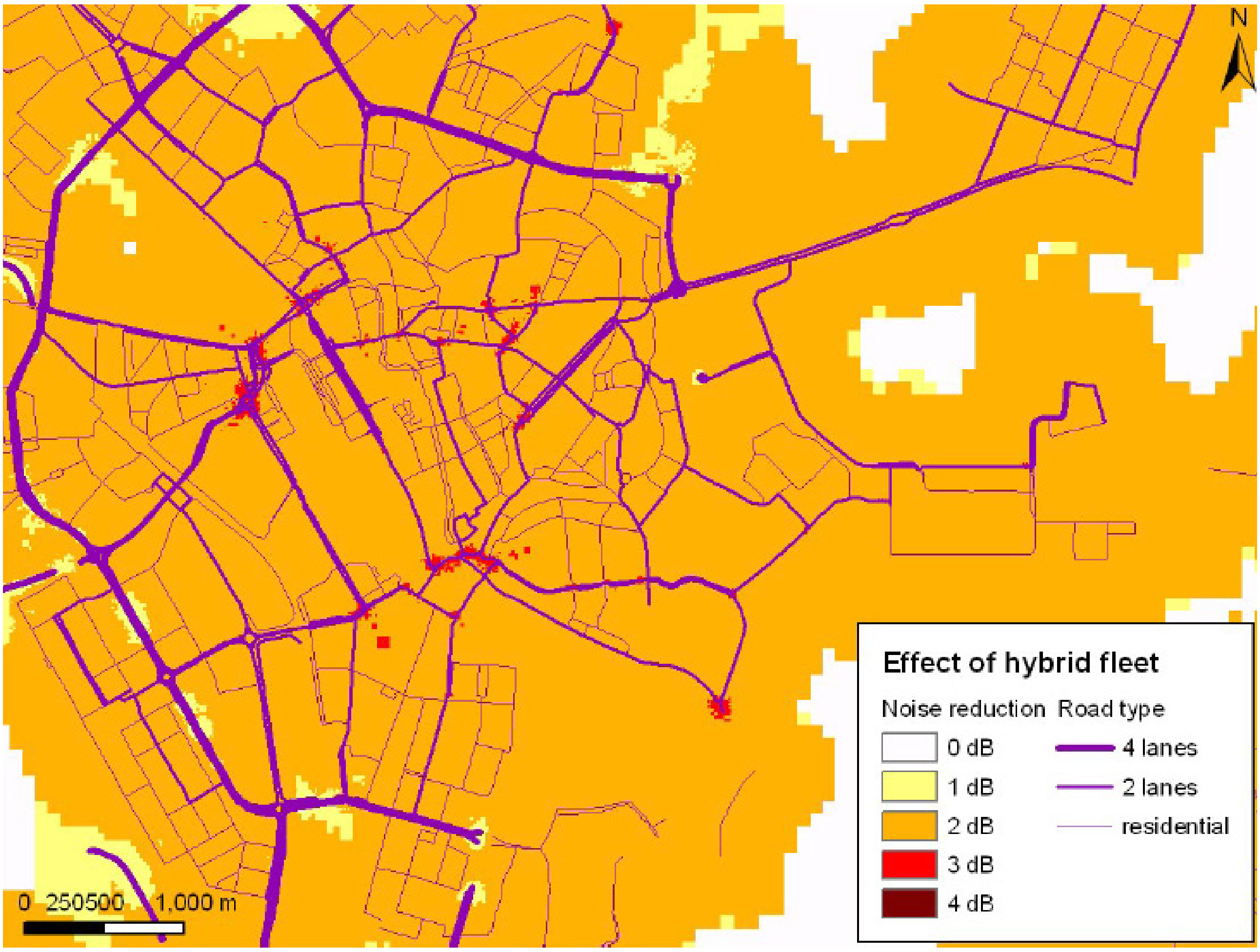

Figure 40:
Noise reduction following replacement of the ICE fleet with a fully hybrid fleet in the city of Utrecht in the Netherlands. This figure is taken from a study by Edwin Verheijen and Jan Jabben presented here with kind permission from Jan Jabben [19].

great a reduction of noise this would entail to noise levels in cities if ICE vehicles are replaced by electric vehicles.

In 2010, The National Institute for Public Health and the Environment in the Netherlands performed a study [19] about the decreases in noise levels in the Dutch city of Utrecht after replacing part of the ICE vehicle fleet with electric vehicles. It was assumed that 90% of the passenger cars and light freight cars were electric and 80% of the heavy trucks. A noise reduction map was made of the entire city noise, where the overall noise reduction was 3 dB. The noise reduction on individual roads depended on the type of road, so a noise reduction map was made, see Figure 40. The largest reduction was 4 dB and this was found on secondary urban roads and at intersections. It was not predicted that the noise on roads where the average speed was above 50 km/h would be reduced since the level of the tyre/road noise would eliminate the advantage of the lower propulsion noise.

Based on the predicted noise reduction and geographical population data, it was then calculated how many people were exposed to different noise levels. Table 5 shows the number of dwellings in Utrecht exposed to different noise levels in the present situation and in the situations with hybrid vehicles and electric vehicles. The total number of dwellings in the area is 120,000. The information about the number of people exposed to different noise levels along with dose-response data for road traffic noise and annoyance were used to calculate how large a reduction could be obtained in the number of citizens who are annoyed by road traffic noise by replacing part of the ICE vehicle fleet with electric vehicles. This gave a reduction of 33% of annoyed citizens and 36% of severely annoyed citizens compared to the situation with no electric and hybrid vehicles.

The same authors continued the studies in the Netherlands in 2012 [12], where it was investigated how much less noise is emitted from an electric car compared to an ICE car. This was used to predict the extent to which the noise level can be reduced in a city. The noise under the bonnet of an ICE car and a hybrid car was measured. This was combined with drive-by measurements of the noise from an electric car and an ICE car and with measurements of tyre/road noise. This combination allowed for a prediction of noise in a future situation in a

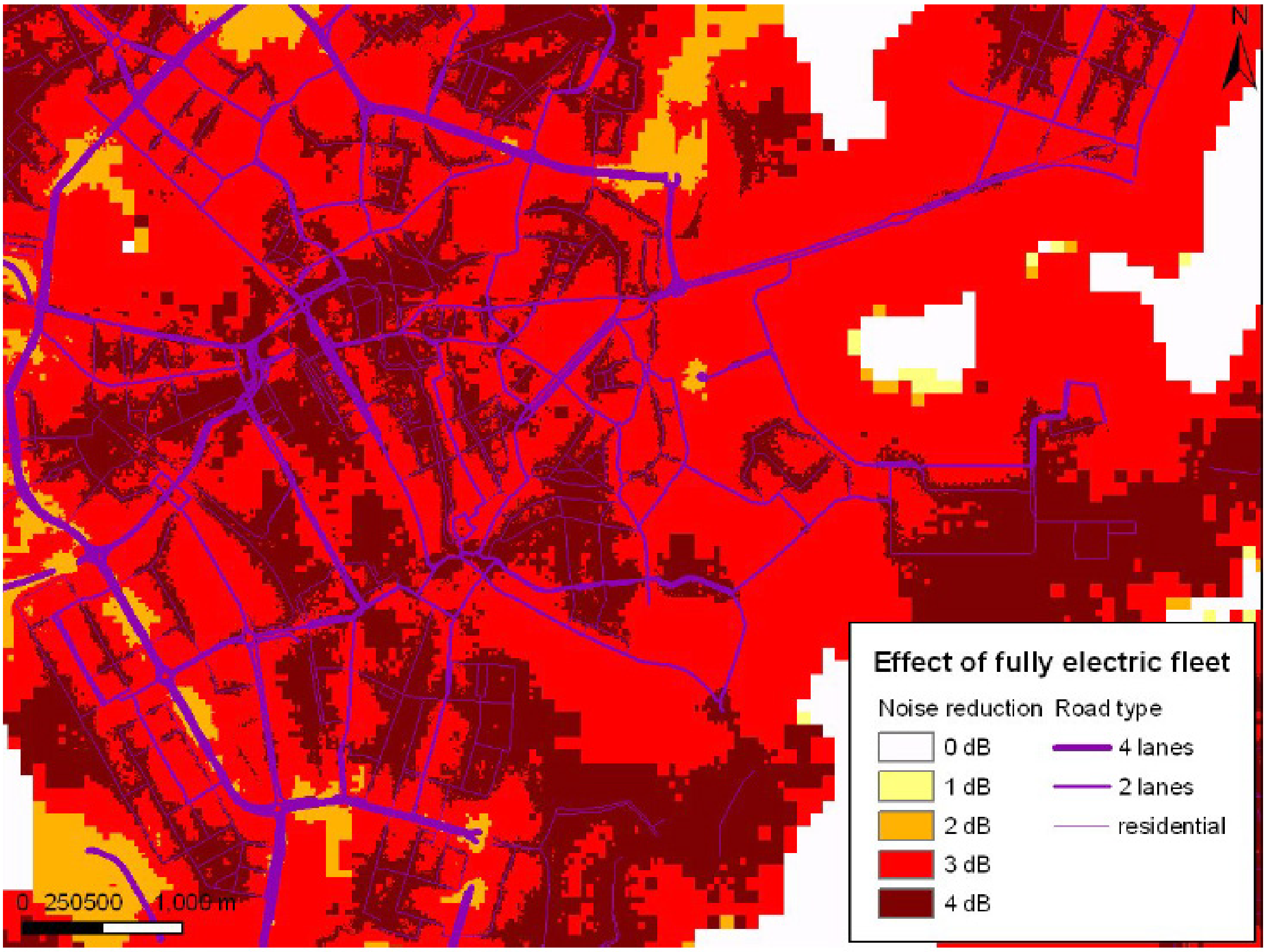

Figure 41:
Noise reduction following replacement of the ICE fleet with a fully electric fleet in the city of Utrecht in the Netherlands. This figure is taken from a study by Edwin Verheijen and Jan Jabben presented here with kind permission from Jan Jabben [19].

Noice class	Present fleet		Hybrid fleet		Electric fleet	
	#	Percentage*	#	Percentage*	#	Percentage*
≤ 54 dB	53600	48%	62300	56%	67000	60%
55 – 59 dB	19700	18%	20500	18%	22400	20%
60 – 64 dB	22300	20%	21000	19%	18300	16%
65 – 69 dB	15100	13%	8100	7%	4400	4%
70 – 74 dB	1500	1%	300	0%	100	0%
≥ 75 dB	0	0%	0	0%	0	0%

Table 5
Number of dwellings per noise class in Utrecht. *Percentage of dwellings exposed to different noise levels in Utrecht. The total number of dwellings is 112,000 [19].

city where 90% of the vehicle fleet was either hybrid or electric. It was expected that 5% of the passenger cars would not be replaced by electric cars and that very few heavy vehicles would be replaced with electric vehicles, so 90% was chosen as an estimate of the replacement of the entire fleet, including heavy vehicles. Silent tyres were also included in the prediction and their influence was estimated as a 3 dB noise reduction in the tyre/road noise. The same result would therefore be obtained if the noise of the surfaces were reduced by 3 dB. The result of the analysis is presented as noise reduction compared to a fleet of 100% ICE vehicles without noise reducing tyres. The result can be seen in Figure 42, which shows that electric cars could mean a significant reduction in the noise level on urban roads at a speed of below 30 km/h, especially if silent tyres are also included. Speed

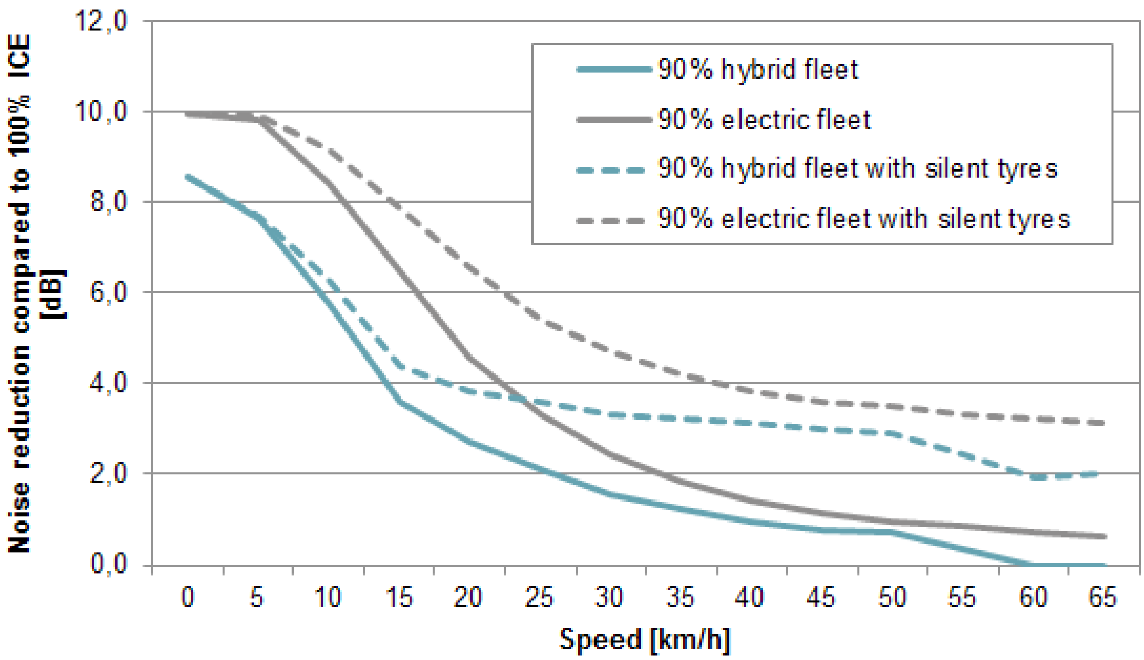

Figure 42:
Prediction of the reduction in the noise level on roads in a Dutch city as a result of introducing 90% electric or hybrid vehicles with and without silent tyres. The noise reduction is shown as a function of the speed of different roads [12].

	Route 1		Route 2	
Tyres	Standard	Silent	Standard	Silent
90% hybrid fleet	-3.0 dB	-4.6 dB	-2.8 dB	-4.5 dB
90% electric fleet	-4.0 dB	-6.1 dB	-3.7 dB	-5.8 dB

Table 6:
Potential noise reduction on two routes in an urban area in a Dutch city. Standard refers to standard tyres and silent refers to silent tyres. From [12].

logs of two test routes in an urban area in the city of Utrecht were used to estimate the effect of introducing electric vehicles in cities. Two test routes were driven in an urban area with two different cars and the speeds of these test routes were logged to predict the potential noise reduction on these routes. The results of the predicted noise reductions on the routes can be seen in Table 6. The assumption about the replacement of the vehicle fleet is the same as used for Figure 42. It can be seen that a noise reduction of up to 6.1 dB can be obtained if 90% of the vehicle fleet is replaced by electric vehicles with silent tyres and up to 4 dB without silent tyres.

An American study from 2012, which was mentioned in Section 7.1 [5], also performed calculations of how the noise level could be lowered by replacing all cars with electric cars. These calculations were based on the REMEL curves presented in Figure 4 in Section 7.1 and standard REMEL curves for other vehicle categories together with the calculated traffic volume on Park Avenue in New York City. The speed which was used was 14.5 km/h, which is based on the average taxi speed in the central business district in 2010. The results are shown in Figure 43 and it is apparent that this study does not predict very large noise reductions, especially at peak hours. In [5] this is explained by the fact that during these hours more buses and trucks populate the streets, and these types of vehicles are not expected to be replaced by electric vehicles. The reduction at night may, however, also be very important, as sleep disturbances are associated with many serious health problems and, since a street must be expected to have many residents, noise reductions at night can be just as important as during the day.

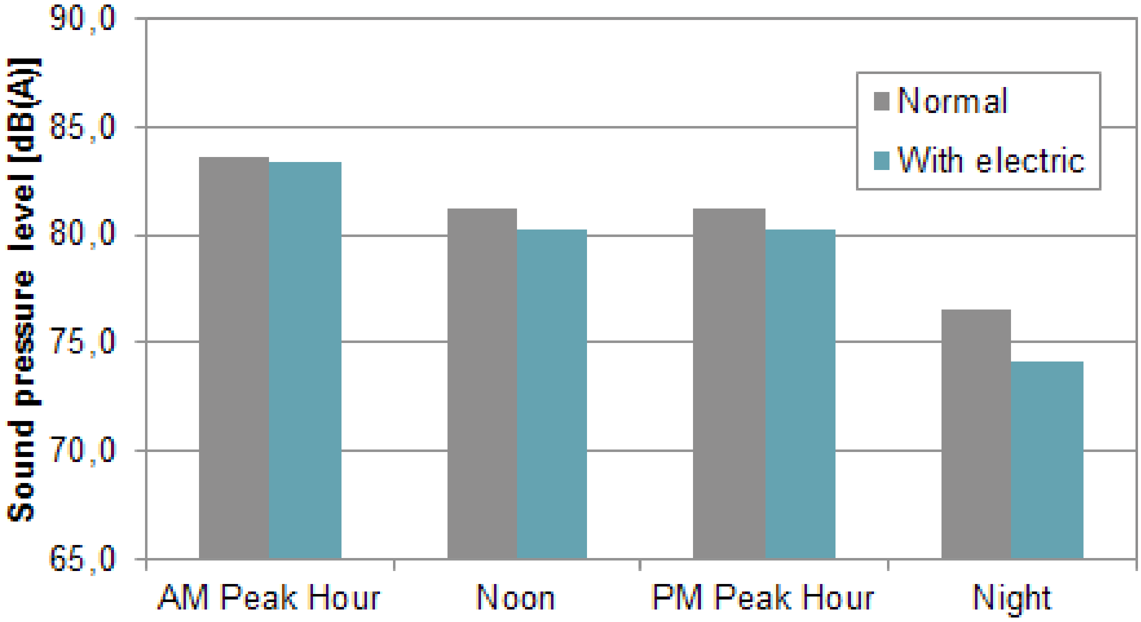

Figure 43:
Current average noise level on Park Avenue in New York City and a prediction of what the noise level would be if all passenger cars were replaced with electric cars, but where heavy vehicles are still using combustion engines [5].

8. Answers to the research questions

In Section 4.2 ten questions were asked in order to help guide this literature survey. In this section the answers to these questions are given based on the literature discovered.

1. Do electric vehicles make more or less noise than conventional vehicles with internal combustion engines?

The short answer to this question is that electric vehicles are quieter than ICE vehicles at low speeds, but not at high speeds. This trend was found in most of the relevant references.

How great the difference is between the noise from electric and ICE vehicles is difficult to say based on the literature found in this survey. It seems to depend very much on the procedure that is used for measuring noise from electric and ICE vehicles and what types of electric and ICE vehicles are used for comparison. Some references state very clearly that as much as possible is done to make the vehicles comparable and some do not specify what vehicles were used. Table 7 attempts to sum up the results for the passenger cars from the references. The second column contains the maximum noise reduction when an electric car is compared to an ICE car. The third column shows the speed above which there is no longer found to be a difference between the noise from an electric car and an ICE car. From the table it can be seen that comparison is not easy, as the measurements were taken at different speeds and at different distances between the cars and the microphone. The only tendency that is seen clearly is that it is only at low speeds that there is a difference in noise between electric passenger cars and ICE passenger cars. A couple of references also found differences at high speeds, but these are much smaller differences than at low speeds. The speed at which there is no longer a difference varies between 25 km/h and 50 km/h.

2. How great is the difference between how much noise different electric vehicles make?

No studies have been conducted to compare noise from different electric vehicles and it is difficult to compare results from different studies as the conditions under which the measurements were taken are different. Some studies included different electric vehicles and if the noise from these is compared it seems that large differences can be found. In reference [6] for instance an electric SUV is found to emit 55 dB at 6 mph and in the same reference an electric mid-size passenger is found to emit 45 dB at 6 mph. Reference [4] measured the noise from two unspecified electric cars and found that at 10 km there is a difference of 3 dB. Differences in tyres will also influence this. So it seems that there can be great differences in noise from different electric vehicles, but more knowledge is needed on the subject.

Reference	Max. reduction	Speed of no reduction	Distance to microphone
[2]	15 dB at 10 km/h*	50 km/h	7.5 m from centre, 1.2 m from ground
[3]	20 dB at idle*	30 km/h	2 m from centre
[4]	7 dB at 10 km/h*		2 m from centre, 1.2 m above the ground
[5]	12 dB at 8 km/h*	24 km/h (difference grows above 45 km/h to 2 dB at 70 km/h**)	
[6][1]	1 dB at 9.7 km/h*	32 km/h	3.7 m from centre, 1.5 m above ground
[6][2]	9 dB at 9.7 km/h*	32 km/h	3.7 m from centre, 1.5 m above ground
[7]	4 dB at 40 km/h	Still 2 dB at 80 km/h**	7.5 m from centre, 1.2
[8]	4 dB at 30 km/h*		
[11]	7 dB at 10 km/h*	40 km/h 7.5 m from centre	
[12]	10.5 at 10 km/h*		3 m from centre, 1.5 m above ground

Table 7:
Reduction in noise when an ICE passenger car is compared to an electric passenger car. *Lowest measured speed, **Highest measured speed. 1This reference compared 'twin' cars and the same is done here for the Highlander (SUV) 'twins'. 2This reference compared 'twin' cars and the same is done here for the Matrix/Prius (regular passenger car) 'twins'.

3. What is known about noise from electric vehicles at different speeds?

As explained in Section 4.1, it was expected that the difference in noise from electric and ICE vehicles would even out at high speeds as the tyre/road noise became more dominant. Most studies confirm this, but the speeds at which this happens are ambiguous. Furthermore there are a few references that found that there still is a difference at higher speeds.

In order to make comparison easier, the noise reduction at the same speeds in different references was compared. Table 8 shows this comparison for 10 km/h, 20 km/h, 30 km/h, 40 km/h and 50 km/h. The fields in the table are blank if the reference does not have any data for that particular speed. It can be seen that at 10 km/h the references predict a reduction anywhere from between 1 and 15 dB and at 50 km/h the difference was found to be between 0 dB and 8 dB. These are not very clear or unequivocal results, but there is a clear tendency in the results from all references for the difference in noise to be greatest at low speeds.

For heavy vehicles there are fewer references, but the two references that were found for trucks driven at constant speeds are summed up in Table 9. It is seen that for heavy vehicles the difference in noise between the electric vehicle and the ICE vehicle is also greatest at low speeds. Neither of the references found, however, that there is a speed above which there is no difference.

4. What is known about noise from electric vehicles on acceleration and braking?

Fewer references with measurements of noise from accelerating and braking electric vehicles were found. Reference [5] found that at full acceleration from 5 mph (8km/h) the difference between noise from an electric vehicle and an ICE vehicle is 7 dB. At 25 mph (40 km/h)

Reference	10 km/h	20 km/h	30 km/h	40 km/h	50 km/h	Distance to microphone
[2]	15 dB*	15 dB*	8 dB*	3 dB*	2 dB*	7.5 m
[3]	7 dB	1 dB	0 dB	-	-	2 m
[4]	6 – 11 dB	0 – 5 dB	-	-	-	2 m
[5]	3 dB	0 dB	0 dB	0 dB	0 dB	
[6][1]	1 dB**	0.5 dB	0 dB	0 dB	0 dB	3.7 m
[6][2]	9 dB**	2 dB	1 dB	0 dB	0 dB	3.7 m
[7]	-	-	4 dB	5 dB	2 dB	7.5 m
[9][3]	-	-	2 dB	-	-	7.5 m
[9][4]	-	-	3 dB	-	-	7.5 m
[9][5]	-	-	3.5 dB	-	-	7.5 m
[9][6]	-	-	4.5 dB*	-	-	7.5 m
[10][7]	-	-	-	-	8 dB	7.5 m
[11]	7 dB	3 dB	1 dB	1 dB	0 dB	7.5 m
[12]	10.5 dB	8.5 dB	6.5 dB	4.5 dB	2.5 dB	3 m

Table 8:
Difference in noise between electric passenger cars and ICE passenger cars. *diesel car used for comparison. **speed=9.7 km/h. [1]This reference compared 'twin' cars and the same is done here for the Highlander (SUV) 'twins'. [2]This reference compared 'twin' cars and the same is done here for the Matrix/Prius (regular passenger car) 'twins'. [3]This reference compared similar cars and the same is done here for the Stromos/Agila pair. [4]This reference compared similar cars and the same is done here for the E-City/Fiesta pair. [5]This reference compared similar cars and the same is done here for the e-Smart Fortwo/petrol Smart Fortwo pair. [6]This reference compared similar cars and the same is done here for the e-Smart Fortwo/diesel Smart Fortwo pair. [7]Many different ICE cars were used for comparison. It was decided to use the small ICE car here.

Reference	Max. reduction	Min. reduction	Distance to microphone
[15]	10 dB at 10 km/h*	1 dB at 50 km/h**	7.5 m from centre
[11]	15 dB at 5 km/h*	2 dB at 90 km/h**	7.5 m from centre

Table 9:
Reduction in noise when a heavy ICE vehicle is compared to a heavy electric vehicle. *Lowest measured speed. **Highest measured speed.

there is no longer a difference between the electric and the ICE vehicle.

The study of the 'twin' vehicles [6] measured the noise from the cars after acceleration over 200 feet starting at 20 mph. The result here was that within the 'twin' pairs there was either no difference in noise or a very small difference. The difference between the pairs was larger, around 1.5 to 2 dB.

The same study [6] also measured the noise from decelerating cars, with deceleration of 1 m/s2 starting 100 feet before the microphone with the result that for one of the 'twin' pairs the electric car was actually 2 dB noisier than its ICE 'twin'. For the other pair the noise from the ICE car was 4.5 dB louder than that from the electric car. As this is the only reference which took measurements of decelerating cars, it is difficult to conclude anything about decelerating electric vehicles.

The Danish Master's thesis [7] found that there was a difference between the noise from the accelerating electric vehicle and the accelerating ICE vehicle of around 4 dB at all speeds. This is the reference which also found differences at high speeds for the vehicles driven at constant speeds.

The CityHush project [10] found a difference of 7 dB between an electric vehicle and an ICE vehicle accelerating from 50 km/h.

Reference [8] found a difference in noise of 8 dB between electric vehicles and ICE vehicles driven in what is called stop-and-go situations in the reference. As mentioned, this stop-and-go situation is unspecified, but it must be assumed to be a situation of acceleration and braking.

For heavy vehicles there are also a few results. Reference [14] measured the noise from electric and ICE buses driven at 25 km/h, braking and then accelerating to 25 km/h again. In this situation a difference of up to 12 dB was found between the electric bus and the ICE bus, the electric bus emitting the lower noise.

Reference [15] contains results for both accelerating and braking heavy vehicles. For accelerating vehicles the difference is up to 6 dB at low speeds and at 40 km/h there is still a difference of around 2.5 dB. For braking the difference is smaller, only around 3 dB at low speeds and above 35 km/h there is hardly any difference.

To sum up the results for accelerating vehicles, the curves of the relation between noise and speed tend to be flatter than those for constant speed, meaning that the noise from accelerating vehicles changes less with speed than the noise from vehicles driven at constant speed. There also seems to be a tendency for the difference in noise between the electric vehicles and ICE vehicles at high speeds to be larger when the vehicles accelerate than when they are driven at constant speeds.

5. Does the difference in the tyres on electric vehicles and conventional vehicles with combustion engines make a difference in the noise emitted?

Most references did not specify what tyres were used on the cars for the measurements and it is therefore difficult to know whether there is a difference in tyres and if that difference in tyres makes a difference in emitted noise. In reference [7] the same tyres were used on the electric car as on the ICE car, so here any potential difference should be eliminated. There was, however, a difference in noise from the electric car and the ICE car at speeds as high as 80 km/h, the speed at which the tyre/road noise should dominate.

Reference [10] contains information about the tyres on the electric cars which were used for measuring, but nothing is stated about the tyres on the ICE vehicles. It is therefore impossible to know whether any differences in noise stem from a difference in tyres.

6. What is known about tyre/road noise compared to engine noise from electric vehicles?

None of the references measured the tyre/road noise from just the electric vehicles, but it was found that the difference in noise from electric vehicles and ICE vehicles is greatest at low speeds. This fact along with the fact that tyre/road noise dominates over propulsion noise for ICE vehicles at high speeds indicates that the propulsion noise from electric motors is very low compared to the tyre/road noise.

7. What is known about the differences in frequency spectrums of the noise from electric vehicles compared to conventional vehicles with combustion engines?

Several references found that frequency spectrums of the noise from electric vehicles can have some peaks at middle frequencies. The noise spectrums from the ICE vehicles can also have peaks but these peaks tend to be at lower frequencies. The peaks at middle frequencies in the noise from electric vehicles can be a problem as noise in this frequency range is more audible to the human ear and they can then be heard as single tones, which can be perceived as annoying.

8. What impact does noise which is artificially added to electric vehicles have on the total noise emission from electric vehicles?

Only one reference was found where measurements were taken of electric vehicles with artificially added noise. In this reference [4] it was found that the total A-weighted sound pressure level from electric cars with artificially added noise was close to that from the quietest ICE car. When looking at the frequency spectrums of the noise from the electric cars with artificially added noise, the added sounds can be seen as very clear peaks at 2.5 kHz. As mentioned in the previous answer, this can become a problem as the noise can be perceived as a single tone.

9. How great an impact can replacing ICE vehicles with electric vehicles have on the overall noise level in cities?

Reference [12] calculated the noise reduction for two routes in an urban area in a Dutch city if 90% of the vehicle fleet is replaced by electric vehicles. This showed that up to 4 dB can be expected with standard tyres and up to 6 dB with silent tyres. The same authors found in 2010 [19] that a fully electric fleet could result in a noise reduction of up to 4 dB in some areas in the city of Utrecht.

Reference [5] predicted the noise reduction on a street in New York City if all passenger cars were replaced with electric passenger cars. It was found that the noise reduction in peak hours would not be great as the buses were not expected to be electrified. At night time, however, a reduction of 2.3 dB was expected and noise at night can affect the health of residents in the street as sleep disturbances are associated with many health problems.

10. What is the noise from hybrid vehicles with both a combustion engine and an electric motor?

Reference [2] and reference [3] found that if a hybrid vehicle is driven in purely electric mode, it emits the same noise level as an electric vehicle. In most of the studies including hybrid vehicles found the hybrid vehicles were driven in purely electric mode. Reference [12] predicted the noise reduction in a Dutch city if electric or hybrid vehicles were used instead of ICE vehicles. It was found here that at low speeds the situation with hybrid vehicles would result in around 1.5 dB less noise reduction than the situation with electric vehicles.

9. Conclusion

The findings in this literature survey show that there is a potential for noise reduction by replacing ICE vehicles with electric vehicles, but the findings also show that there is a great deal of uncertainty about how large this potential is. The reduction in noise found in the references differs greatly and seems to depend very much on how the comparison between the noise from ICE vehicles and electric vehicles is carried out. Most references do, however, confirm the assumption that it is only at low speeds that noise reduction can be expected. However, at what speed this is and what the result would be to noise levels in a city is not clear from the findings.

There is a tendency for electric cars to be smaller than most ICE cars and in some cases the comparisons were carried out with cars that were not of equal size, which could influence the results. When very similar cars are compared lower reductions are seen. For instance, in the American study of 'twin' cars small differences were seen, especially when considering the SUV 'twins'.

A large potential for noise reduction by electric trucks was found by two references. This is, however, a subject which has been investigated far less than noise from electric passenger cars.

The findings about the frequency content of noise from electric vehicles generally show that there can be some peaks at middle or high frequencies, which have the potential to be heard as single tones and therefore be perceived as annoying. This is also confirmed by some reported experiences from electric cars, but no thorough subjective investigation has been found which can validate this.

References predicting the potential noise reduction in cities were also found. These show that a reduction of anywhere between 0 dB and 6 dB can be obtained if silent tyres are also used. These results are based on measurements of the noise from a few vehicles and a chosen city, street or route in an urban area. The expected reduction therefore seems to depend very much on the chosen example and the vehicles used for estimating the noise reduction by a single vehicle.

9.1 Recommendations for future measurements

More knowledge is needed on the tyres used on electric cars. Many of the references found in this study were very unspecific about the vehicles used for measuring, including the type of tyres used on the vehicles. One reference was very specific about the fact that the exact same tyres were used on both the electric and the ICE car, but this reference found a difference in noise from the electric car and the ICE at high speeds, which is rather strange as the tyre/road noise should dominate the propulsion noise at these speeds. This indicates that further measurements and more knowledge are needed on tyre/road noise from electric vehicles. To fully explore the subject, it would also be relevant to examine what types of tyres are generally used on electric cars.

In most of the references there was no information about the road type which the measurements were carried out on and none of the references used different types of road surface for comparison. To be able to predict a reduction in the sound level in a city, knowledge of the different types of road surfaces in the city is needed. A high noise surface can mean that the tyre/road noise is more dominant at lower speeds than it would be on a low noise surface and there can therefore be a difference in how great a noise reduction can be obtained. The same is also true for the tyres on the vehicles. Therefore, an investigation of the influence of the road surface on the tyre/road noise is needed.

Another course of action which could help determine how much of the noise reduction is due to just the electric propulsion would be to take more measurements of the propulsion noise.

Which types of ICE vehicles are used for comparison should be considered. For example, a comparison could be made of new ICE vehicles with new electric vehicles, if it is assumed that the people who buy electric vehicles would have bought a new ICE vehicle had they not chosen to buy an electric vehicle. A comparison could also be made of the current vehicle fleet with electric vehicles.

Measurements of different driving situations such as acceleration, braking and reversing are needed. If the noise reduction in a city is to be predicted, then a thorough investigation is also needed of the driving patterns. One reference assumed that the driving pattern in a city corresponded to driving partly at 50 km/h and partly accelerating from 50 km/h. This would, for many cities, be an overestimation of the speed and the amount of acceleration. One reference found that the average speed in an urban area was 22 km/h, but no information was given about the amount of acceleration or the amount of time the car spent standing still.

Heavy vehicles also show a great potential for noise reduction as a result of replacing ICE vehicles with electric vehicles. More knowledge about whether or not it is realistic to replace these with electric vehicles is needed. Electric buses especially could be interesting as these are often present in urban areas.

A new standard for measuring noise from low noise vehicles is on its way. It is called “Measurement of minimum noise emitted by road vehicles” and it proposes measuring the noise at a distance of 2 m instead of the 7.5 m stated in the current standards regarding pass-by measurements. As it can be seen from the findings it would be preferable if there was a standard way of taking the measurements in order to make different results more comparable.

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