NVH Analysis Techniques for Design and Optimization of Hybrid and Electric Vehicles
Chapter 4
Sound Quality of Electric vehicles

Etienne Parizet [1], Karl Janssens[2], Pedro Poveda-Martínez[3], Andreia Pereira[4], Jakub Lorencki[5] and Jaime Ramis-Soriano[3]

[1]LVA, INSA-Lyon, Villeurbanne, France, etienne.parizet@insa-lyon.fr
[2]LMS International NV, Leuven, Belgium, karl.janssens@lmsintl.com
[3]University of Alicante, Alicante, Spain, jramis@ua.es, pedro.poveda@ua.es
[4]University of Coimbra, Coimbra, Portugal, apereira@dec.uc.pt
[5]Politechnika Warszawska, Warszawa, Poland, j.lorencki@mechatronika.net.pl

Abstract. Despite being an important step in the fight against environmental pollution, electric vehicles and hybrid electric vehicles present some doubts. The low level of noise emitted by the propulsion system implies an increased risk for pedestrians, especially at low speeds. The Competent Authorities, as well as the scientific community and industry, are addressing the problem to stablish a common legislative framework regarding road safety. The most significant proposal is the use of Acoustic Vehicles Alerting Systems (AVAS) in order to increase detectability of quiet vehicles.

The aim of this chapter is to collect the main contributions regarding sound quality of hybrid electric vehicles and electric vehicles. As a started point, a state of arte is presented to contextualise the problem of quiet vehicles. Contributions included in this document refer to both inside and outside sound quality.

1 Introduction

At low speed, electric vehicle are very quiet, when compared to gasoline or diesel engine cars. The noise level difference between an electric vehicle and one with an internal combustion engine can be as large as 6 dB(A) at 10 km/h [1,2]. This difference becomes smaller at higher speeds. Above 40 km/h (approx.), both types of cars are equally loud, as tires become the dominant noise source.

This low noise level can be a safety issue for pedestrians, are they may not be able to detect an approaching EV, due to a strong masking effect of the ambient urban noise. This was confirmed by an in-situ experiment [3]: twelve visually impaired people had to detect an approaching car, driving on a very smooth road surface at a maximum speed of 30 km/h. At very low speed (10 km/h), EVs were detected only a few meters from the subjects. The real consequence on accident rates is still unclear, due to the reduced number of electric vehicles on the roads in the past years. In 2009, a study made by NHTSA [4] claimed that the incidence rate of pedestrian crashes was 0.9 %

for EVs or HEVs, as compared to 0.6 % for ICE vehicles. But, at the time of the study, 8 400 EVs only were on the road in the United States. This study was updated in 2011, but the low number of data regarding electric vehicles was still true [5]. Moreover, a Dutch study published in 2010 found no evidence of a greater safety risk for EVs or HEVs [6].

Nevertheless, there is no dispute that this very low noise level prevents visually-impaired or blind people from being aware of an approaching electric car. This strongly reduce there ability to walk in a city. In order to solve this issue, additional warning sounds have to be used on such vehicles. These sounds are emitted by a loudspeaker located at the front of the vehicle (typically in the engine compartment). The main question is then related to the sound itself, which should be designed so as to be easily detected by pedestrians, while keeping a low level. Beside the safety issue, the warning sound should not be unpleasant and convey a brand image.

While many papers about alarm sounds in work environments have been published (airplane cockpits, intensive care units or machinery rooms; see [7] for a review), only few studies have focused on warning sounds for low-noise vehicles. Yamauchi et al. used three warning sounds (engine noise, car horn and band-pass noise) in a laboratory study involving German and Japanese listeners [8]. The audibility of each sound was measured in different background noises. Results indicated a strong influence of the kind of warning sound, depending on the background noise. The difference reached up to 10 dB between the band-pass noise (which was the most easily detected sound) and the car horn. No cross-cultural difference in detectability emerged. Wall Emerson et al. [9] conducted an in-situ experiment for which five artificial sounds were synthesized and played back by a loudspeaker mounted to an electric vehicle. Fifteen blind participants were seated at the side of the roadway and were asked to indicate when they detected the arriving car (at a speed below 20 km/h). Several trajectories were investigated (the car was moving on a straight line, or was making a right turn, etc.). Differences in the effectiveness of the five warning sounds in communicating these manoeuvers were observed; unfortunately, the report fails to provide information about the levels of the warning sounds or other replicable acoustical specifications. The authors advocate that efficient warning signals should (a) have maximum energy around 500 Hz and (b) be amplitude modulated. Misdariis et al. used 10 sounds, which could be represented in a two-dimensional timbre space [10]. The first dimension was related to temporal modulation and the second one to spectral flatness (distinguishing a random noise from a tonal sound). The amplitude of the signals was modified so as to simulate an approaching source at 20 km/h. Six participants had to detect each sound in a background noise. Again, there were strong differences in the detectability of the sounds: the shortest reaction time (RT) was obtained for a siren sound (4 s) and the longest RT (11 s) for a modulated electric hum. Furthermore, there was evidence for differential learning effects.

Between 2010 and 2014, a European funded project (eVADER) aimed at developing a prototype electric vehicle including an automatic pedestrian detection device and an array of speakers focusing a warning sound in the direction of the pedestrian. [11]. was partly devoted to the definition of warning sound timbre. The main question was the following: “given the background traffic noise of an urban environment, is it possible to make a warning sound easily detectable in spite of a low level?” The results show in [12] reveal that is possible to improve the detectability of electric vehicles by using warning sound systems without increasing the environmental noise.

2 State of art.

2.1 Perception of noise from Vehicles.

The vehicle noise can be produced by several sources related to different parts of the vehicle. Some of them will be present depending on the propulsion method used. The effect of these sources may be more or less important depending whether the receiver is placed inside or outside the vehicle.

The following paragraphs describe the main sources of noise for ICV, EV and HEVs.

2.1.1 Noise generated by IC Vehicles.

For a long time the engine has been considered as the main source of noise in vehicles. For this reason, numerous studies have been conducted to reduce noise and vibrations generate by the engine and powertrain. Consequently, current engines and powertrain systems show a strongly reduced level of noise, and other sources such as tired-road noise or aerodynamics become important.

Engine and powertrain

The vibrations produced by the engine are due to the reciprocating and rotational masses within it. Clear examples of these components are pistons, connecting rods and shafts. At the same time, the gearbox and the differential, jointly with the structural modes of the exhaust system, act as sources of vibrations.

Regarding airborne noise, a large number of components are involved in this phenomenon. Special attention should be paid on the intake and exhaust tailpipes. However, sources like the vibrating panels of the engine body, pumps or belts and chains, cannot be overlooked.

Suspensions

The suspension is responsible to connect the tires with the powertrain. Therefore, it constitutes a structure-borne transmission path. The vibrations produced due to the tire-road contact are transmitted to the vehicle. Suspension should act as a filter of these vibrations, preventing them from being transmitted to the vehicle body.

Tires

The tires are in charge of keeping the contact between the vehicle and the road and play a double rule on the noise generation. On the one hand, the surface shape of the tires that is in contact with the road constitutes an important source of airborne noise. On the other hand, the dynamic behaviour of the tires enables the transmission of forces between road and wheels. Thus, vibrations are transmitted to the vehicle by means the structure-borne path.

As the speed increases, the tired-road noise becomes more relevant and begins to overcome the propulsion noise [13].

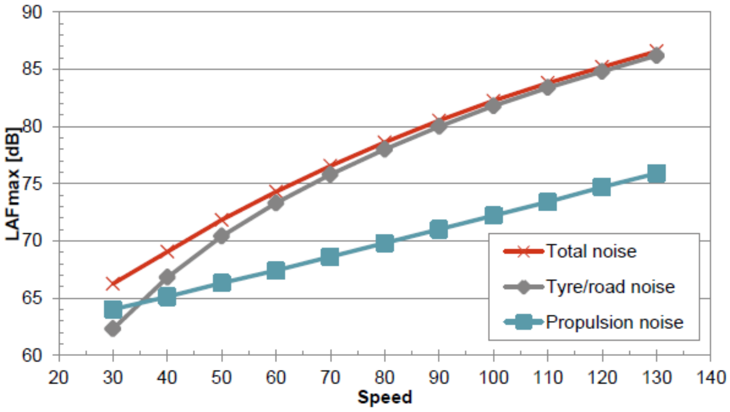

Fig. 1. The propulsion noise, the tyre/road noise and the total noise from a passenger car calculated with the Nord2000 noise prediction model, according to reference [13].

Aerodynamic sources

At high-speed regimens, aerodynamic is the main source of noise. It should be remembered that the intensity of the aerodynamic noise is proportional to the sixth power of the speed. Three different types of sources can be distinguish: a global flow, with influence in the low-frequency range; local flow, present in mid- to high-frequency range; and turbulence, a broadband noise.

Squeaks and rattles from interior dashboard and trimmings

The vibrations produce by the road and the powertrain give rise to the appearance of indirect sources of noise. Some of these new sources are related to the dynamic displacement of the interior surfaces (e.j. the dashboard). The noise is produced by the switching between contact and slipping of several surfaces. This noise is normally located in the high-frequency range.

Other sources

In addition to the sources of noise discussed so far, numerous parts of the vehicle such as breaks or other electrical/mechanical accessories can be considered as secondary sources. Nevertheless, these should be take into account to study the acoustic behaviour of vehicles.

2.1.2 Noise generated by EVs and HEVs.

The noise signature from an electric motor is characterised by speed-dependent high frequency tonal components from the dominating electro-magnetic harmonics, covering a wide rpm-range. Although this system is quitter than ICEs is necessarily not preferable.

We can find different types of electric motors but permanent-magnet synchronous motor is the most popular due to its characteristics. In this system, a DC voltage provided by the battery is converted to a magnitude and frequency controlled AC voltage on the inverter by pulse-width modulation (PWM). The switching frequency for the PWM is constant and in many EVs is located in the range 5-20 kHz. This switching frequency, together with the magnet noise from electric powertrain, are the main contributions to the audible noise in EVs. Other characteristic source of noise of EVs is the sound emitted by funs for battery.

Focusing on the outside noise from the vehicle, this is mainly due to the contribution of two sources: the propulsion system and the contact between tires and the road. As the speed increases, the noise emitted by the tire/road contact becomes highly important, even above the propulsion one. There is therefore a reasonable prospect that if tires used on electric and ICs vehicles are the same, at low speed the noise emitted by the electric one will be lower. A study performed by Joel Lelong and Roger Michelet corroborates this behaviour.

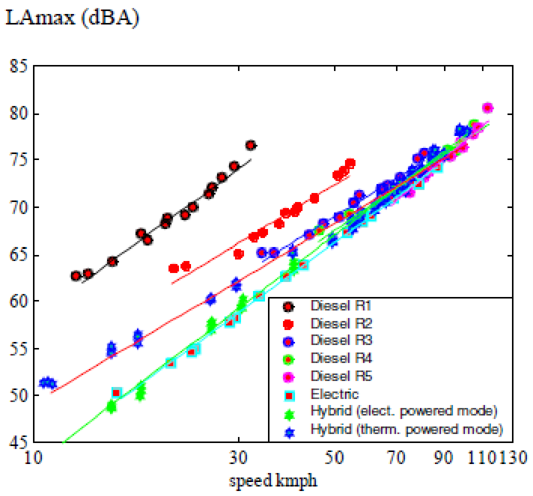

Fig. 2. The maximum noise level from different types of cars measured with pass-by measurements. From a French study by Joël Lelong and Roger Michelet, according to [13].

The study shows that at very low speeds the noise from the EV can be significantly reduced, but at speeds above 50 km/h the difference is negligible. Furthermore, a hybrid car driven in electrically powered mode emits the same level of noise as the purely electric car.

Another study conducted by Sakamoto, H. Houzu e al. in 2012 shows 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, especially in the middle and high frequencies.

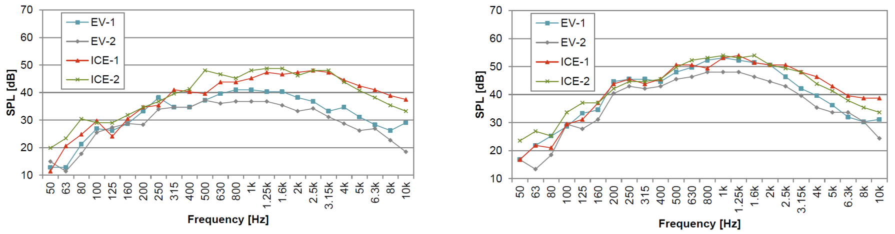

Fig. 3. The A-weighted frequency spectrums for ICE and EV vehicles driven at a constant speed (left 10km/h - right 20 km/h) according to [13].

If the noise reduction generated by electric vehicles occurs only for low speeds and at the same time in acceleration, deceleration and braking regimens, then it is important to evaluate its behaviour in cities, where such situations are more common. Although electrical cars may offer advantages in noise reduction, other factors related to the emitted noise should be analyzed. The spectral content of the noise emitted by electric vehicles can influence the way in which sound is perceived. The emission of pure tonal components by the electric engine can be perceived as annoyance. Also, the noise reduction due to the electrical powertrain at low-speeds can affect the detectability of vehicles and thus pose a risk to the safety of pedestrians and cyclist. The solution of adding artificial noise to some electric vehicles in some driving and speed situations has been employed. The evaluation of this noise needs to be considered.

2.2 Sound Quality Metrics.

The acoustic metric to evaluate noise outside the vehicle corresponds to the sound pressure level in dB(A). The ISO standards available to measure the sound level emitted by vehicles under *typical urban traffic environments* are:

- ISO 362-1 Measurement of noise emitted by accelerating road vehicles - Engineering method - Part 1: M and N categories (passengers cars and light vans) [14].
- ISO 362-2 Measurement of noise emitted by accelerating road vehicles - Engineering method - Part 2: L category (heavy vehicles) [15].
- ISO 362-3 Measurement of noise emitted by accelerating road vehicles -- Engineering method - Part 3: Compatibility between indoor and outdoor testing of road vehicles [16].

The European Parliament and of the Council of 16 April 2014 has publish in the Journal of the European Union the Regulation (EU) No 540/2014 on the sound level of motor vehicles [17]. This regulation introduces some guidelines related to hybrid vehicles and Acoustic Vehicles Alerting Systems. In the same vein, the Informal Group on Quiet Road Transport Vehicles QRTV, form United Nations, is working on the harmonising of rules related to EVs and HEVs. Therefore, it is expected a new kind of sound quality metrics in future to evaluate the noise emitted by quite vehicles.

2.3 Warning Sounds.

Electric vehicle warning sounds are sounds designed to alert pedestrians of the presence of electric drive vehicles travelling at low speeds. In these circumstances, Electric vehicles produce less noise than traditional combustion engine vehicles. This phenomenon makes them more difficult to detect for pedestrians and cyclists, especially for blind people. The use of an Acoustic Vehicle Alerting System can avoid the problem effectively.

2.3.1 Identification of dangerous scenarios.

According to [18], study conducted by the National Highway Traffic Safety Administration (NHTSA), HEVs are two times more likely than ICE vehicles to be in a pedestrian crash in the following situations:

- Backing out;
- Slowing/stopping, starting in traffic;
- Entering or leaving a parking space/driveway;
- Turning.

This study also concluded that vehicles involved in such crashes are likely to be moving at low speeds. In this situation, the sound level emitted by HEVs and ICEs is substantial different. The crash incidence rate for the combined set of manoeuvres is 1.2 % and 0.6 % percent for HEVs and ICE vehicles respectively.

A reduction in the sound level emitted by vehicles, operating in electric mode at low speeds, may have implications for all pedestrians. Blind people, who depend almost entirely on auditory cues to moving around the city, may be particularly affected. For this reason, some organizations have expressed concern about the lack of sound emitted by HEVs.

2.3.2 Regulations.

The problem introduced by the EVs and HEVs has encouraged the European Commission, the U.S. Congress and the Japanese government to work on specific legislations. The first guidelines are aimed to stablish a minimum level of noise emitted by the electric vehicles circulating at low speeds.

American Standards

In the United States the discussions and legislations are on the uttermost advanced level prepared and discussed by two very influential parties - U.S Department of Transportation and National Highway Traffic Safety Administration (NHTSA).

In 2010, U.S. Senate approved The Pedestrian Safety Enhancement Act [19]. This law encourage the U.S. Department of Transportation to research the topic and conceived a new alerting system to ensure safety of pedestrians. The act was finally signed by President Barack Obama at the beginning of 2011.

In January 2013 NHTSA, after some research, stablish the necessity of additional noise for vehicles at speeds below 30 km/h [20]. Vehicle manufacturers may design their own warning sound with certain restrictions. The sound should be similar to the noise emitted by an IC vehicle. The warning sound should be mandatory and the driver cannot turn it off manually. Despite the fact that this regulation was approved during 2014, manufactures has a three-years period after the date of publication to adapt their vehicles to the requirements.

Other suggestions have been proposed. The Association of Global Automakers and the Alliance of Automobile Manufacturers consider that the noise level of the warning sound cannot be disturbing. Hence, it may not affect people inside cars as well as the other participants in road traffic.

Japan Regulation

In 2010, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) published a Guideline for the Approaching Vehicle Audible System, focus on the HE/HEVs problem. This guideline establish some requirements for the AVAS as the types of sounds emitted, the volume or operation time. At the same time, it provides some indications related to the installation of warning sound systems.

European Union

The European Union has been working on a system named AVAS – Acoustic Vehicle Alerting System. This project aims to develop a warning sound system involving the vehicle manufacturers. This system is supposed to be used at speeds under 20 km/h.

In April 2014, the European Parliament approved a legislation that requires the use of Acoustic Vehicle Alerting System in all new electric and hybrid electric vehicles [21]. A transitional period of 5 years was established to comply with the regulation. This document sets out the following measures concerning the AVAS for hybrid electric and pure electric vehicles:

Sound generation method:

The AVAS should automatically generate a minimum sound in the range of speeds from start up to approximately 20 km/h and during reversing. For hybrid vehicles operating in combustion mode within the speed range defined above, the AVAS shall not generate a sound.

The system should be fitted with switch. This will be easily accessible by the vehicle driver in order to allow its activation and deactivation. Upon starting the vehicle, the AVAS should be switched to the default position.

Sound type and volume

A continuous sound should be emitted. It should be similar to the sound radiated by a vehicle of the same category equipped with an internal combustion engine. The sound level generated by the AVAS is limited to the sound level of a M1 category vehicle equipped with an internal combustion engine and operating under the same conditions.

2.3.3 Basic characteristics of the warning sounds.

According to the United Nations informal Group on Quiet Road Transport Vehicles (QRTV) guidelines [21], warning sounds should present some requirements. Concerning the safety, sounds should be focus on the audibility, locability and directivity. Taking into account the environmental character of sounds, these should be described in terms of directivity, attenuation and acceptability.

Audibility: a frequency band from 0.5 kHz to 3.5 kHz is recommended for optimal audibility.

Locatability: a frequency band from 0.5 kHz to 4 kHz is recommended. The range 0.5 to 1.5 kHz provides interaural phase differences, so indicates to the listener the angle from centre line. Frequencies up to 3 kHz provides interaural SPL differences and give an idea of the source position, left or right. Above 3 kHz, frequencies provide information related to the front or rear position as they affect the Head Related Transfer Function.

Directivity: defines, at any given frequency, how is relative sound pressure level around the source. Low directivities can negatively influence to the environmental behaviour. On the contrary, a high directivity can be bad from the safety point of view, since pedestrians positioned in one side of the vehicle will not receive a good warning signal. At the same time, a system radiating in all directions can influence the detectability of other vehicles masking them. A SPL guideline reduction of 3 dB(A) at +/- 45° and up to 10 dB(A) at +/- 90° is suggested to provide audibility at a safe distance. In addition, sound should drop rapidly on the sides and rear of the vehicle.

Attenuation: for optimal attenuation, a frequency band from below 1 kHz to above 5 kHz is recommended.

Acceptability: in order to not increase the noise pollution and not alter the soundscapes, the warning sounds should be carefully designed. It is recommended that the sound contains similar characteristics to the sound emitted by an ICV.

2.3.4 Metrics to evaluate warning sound systems.

Minimum sound pressure level

A new standard to measure noise from low noise vehicles is being prepared: ISO/CD 16254:2012 “Measurement of minimum noise emitted by road vehicles” [22]. This act proposes a method to measure the minimum noise emission of road vehicles. Besides, includes quantifying the characteristics of any external sound generation system installed. It proposes measuring the noise at a distance of 2 m instead of the 7.5 m that stated in the current standards regarding pass-by measurements.

Other parameters

The NHTSA [20] proposes a set of parameters and minimum requirements that EVs and HEVs must comply in order to allow pedestrians detect presence, direction, location and operation of the vehicle. Table 1 sums up the sound parameters and requirements that are analysed.

Table 1. NHTSA parameters and minimum requirements.

Sound Parameters	**Alternative 1 (No Action)**	**Alternative 2 (Preferred Alternative)**	**Alternative 3**
Min. Sound Required	No	Yes	Yes
Applicable Speed	N/A	Idle to 30 km/h, reverse	> 0 to 20 km/h, reverse
Broadband Low Frequency Sounds	N/A	160 – 5000 Hz	N/A
One-Third Octave Bands	N/A	Minimum sound pressure levels (SPLs) for eight specific band sets between 160 and 5000 Hz for idle, reverse, and every 10 km/h up to 30 km/h. It must include at least one tone below 400 Hz and one tone that is 6 decibels (dB) above the EV/HV's existing sound level in that band	At least two with SPL of 44 A-weighted dB. One band each in the ranges of 150-3000 and 500-3000 Hz.
Pitch Frequency Shift with Acceleration & Deceleration	N/A	1% per km/h	15% monotonic shift between 5 and 20 km/h
Total Minimum Sound Levels Resulting from the Individual Minimum Sound Requirements	N/A	Idle – 49 dB(A) Reverse – 52 dB(A) 10 km/h – 55 dB(A) 20 km/h – 62 dB(A) 30 km/h – 66 dB(A)	48 dB(A)

2.3.5 Technologies to generate warning sounds.

According to the technical report of NHTSA [23], the warning sounds could be based on recordings of actual ICE vehicles. A second alternative is to generate the sound by means of a digital signal processor chip programmed to emulate the sounds of an ICE. This alternative would permit a wider range of sounds taking as a reference ICE noises.

Finally, another option could be the use of digital signal processors to create simultaneously both ICE noise as sounds that embody special characteristics to enhance detection.

Since the most legislation is still being drafted, many manufacturers have started to develop their own warning sound systems. Brands like Toyota, General Motors or Nissan are beginning to install their devices in the new EVs/HEVs.

Toyota Motor Company

In 2010, Toyota initiated to sale a device for Prius model. This device was prepare to emit a warning sound when the vehicle is operating in electric mode up to approximately 25 km/h. As the speed of the vehicle changed, the system changed the pitch. Toyota introduced the system on the U.S. market in 2012 by means of the Prii family vehicles. The device was called Vehicle Proximity Notification System (VPNS).

General Motors

GM's system, called Pedestrian-Friendly Alert System, appeared for the first time in the hybrid vehicle Chevrolet Volt, in December 2010. This system was design to be activated manually.

Hyundai

Hyundai developed their own system, called the Virtual Engine Sound System (VESS), in September 2010. This system emulated the sound of idling internal combustion engine. The Company started to install the system in the Hyundai Sonata Hybrid series.

Lotus Engineering

Lotus engineering, a consultancy group of Lotus Cars, teamed up with Harman Becker in 2009 in order to produce and sell synthetic automotive sound systems. The project generally was involved with all the sound of the vehicle, with particular emphasis on warning sounds for hybrid/electric vehicle. Lotus adopted the idea of mimicking the sound of ICE engine, modulating its sound with the speed changes. The system was presented during the Geneva Motor Show in 2010, using a Lotus Evora 414E Hybrid. The system was called HALOsonic.

Nissan

Nissan has the most developed and described warning sound system. It is called Vehicle Sound for Pedestrians (VSP). The system was introduced in the Nissan Leaf and the Nissan Fuga in 2011 [26, 27]. The design included different sound for forward and backward motion.

Nissan's VSP emits a sine wave on the range from 600 Hz to 2.5 kHz. The sound changes as the vehicle is accelerating or decelerating. During acceleration, the system works until reaching 30 km/h. Originally the warning sounds could be turned off by the driver. However, due to the NHTSA guidelines, Nissan removed the switch used to disconnect the warning sound system. On the contrary, the switch remained in U.K. to comply the regulation of this country.

Other Initiatives:

Companies and scientific community have proposed other initiatives. As an example, we have the Vehicular Operations Sound Emitting Systems (VOSES) designed by Enhance Vehicle Acoustics Company (EVA) from Silicon Valley; the ECTUNES system from Horsens, Denmark; Soundracer EVEES from Sweden or Fisker Automotive from California. Each device implements their own hardware and software characteristics, adapting the system to the current guidelines.

3 Challenge and future work

For car industry acousticians, electric vehicles represent a new challenge, as engine noise sources are quite different from the ones these acousticians are used to analyse [28, 29, 30]. As regards sound quality, three important issues are the following ones:

1) Prominent tones

Rotating parts (electric engines, inverters, transmission…) produce high frequency tones (see figure 4.)

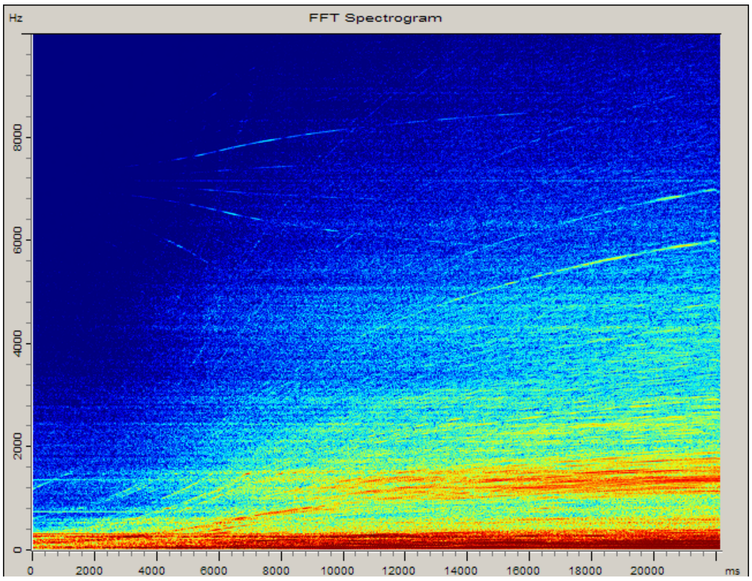

Fig. 4. Spectrogram of a run-up measured in an electric vehicle

It is well known that prominent tones contribute to unpleasantness [24] and that this is particularly true for high frequency tones [25]. Some metrics exist for evaluating the prominence of each individual tone (Tone-to-Noise Ratio or Prominence Ratio), as defined in standards (e.g. DIN 45681-2002 or ISO S1.13-1995). A more complex metric (Aures' tonality) aims at evaluating the tonalness of a sound in which several tones can be detected. But the knowledge of the relation between this tonalness and the sound quality still needs to be improved.

2) Sound information

In an ICE vehicle, sound from the engine provides information to the driver. Objective information relates to the behaviour of the engine (people get used to evaluate the speed by listening to the engine), but the sound also provides an image of the engine powerfulness. As this information is no longer present in an EV, which cues are used by drivers? Some inquiries should be conducted in order to identify these relevant element and to know whether it is necessary to provide these elements using, as an example, audio devices.

3) Warning sounds

Clearly, there is a need for warning sounds, in order to increase the safety of electric vehicles. But these sounds should be as less loud as possible, because EVs represent a unique opportunity to reduce noise annoyance in cities. Regulations to be decided should provide a compromise between these two requirements.

In the short and medium term, it is expected that the number of EV and HEVs will remain rather low. This will make the effect of such cars on urban noise level rather small – meaning that warning sounds can be rather loud in a first step. But this level will have to be reduced as the proportion of silent vehicles will increase.

Warning sounds can be defined by sound designers, which will allow car manufacturers to give a brand image to these warning sounds. Indeed, this is the first time car manufacturers car fully design the outside noise of their vehicles. But, on the other hand, the sound must clearly evoke an approaching vehicle. So it can be expected that the sound image of an electric vehicle will be progressively defined and that warning sound will share some characteristics closely related to this image.

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Annex 5A

Sound Quality inside Electric Vehicles

Matuszewski, Mateusz[1], Parizet, Etienne[2]

[1]Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche, Ancona, Italy, m.matuszewski@univpm.it

[2]LVA, INSA-Lyon, Villeurbanne, France

Abstract. For a long time, the automotive industry has been researching about sound quality of vehicles. Because of this work, a large set of metrics to evaluate noise inside and outside cars have been developed. The appearance of electric motors into the vehicle fleet has signified a substantial change, specially related to the noise emitted. Due to this situation, internal and external perception of noise has been modified, calling into question the validity of traditional sound quality metrics to evaluate electric vehicles. This contribution aims to study the unpleasantness of the noise emitted by electric engines inside the vehicle. At the same time, it implies the validity of the current sound quality metrics on the new situation.

5A.1 Introduction

The incorporation of electric engines to the automotive market has signified a change into the sound inside the vehicles. This kind of propulsion system exhibits certain features significantly different from an internal combustion engine car. One of the main characteristics is the appearance of high-level tonal components.

This contribution aims to study the unpleasantness of the sound emitted by electric engines inside the vehicle. At the same time, it implies the validity of the current sound quality metrics on the new situation.

The study is based on two listening test: absolute evaluation and pairwise comparison. For carrying out the experiments, recorded sounds from an electric vehicle were used. Bandstop filters were applied to the recordings in order to reduce the level of specific components. The resulting sounds make up the set of stimulus used to evaluate the unpleasantness perceived by listener.

5A.2 Methodology

Experimental Setup.

The listening tests took place in a sound-insulated listening room. Listeners remained seated in front of a table with a flat screen. Sounds were played back over Sennheiser

HD600 headphones by a computer. The PC, equipped with an external RME Fireface UC sound card was placed outside the room. Before presentation, each stimulus was measured using a calibrated MK1 Head and Torso Simulator. Thereby we ensure a correct equalization of the sounds emitted.

Subjective test

Two different methods were used to assess the unpleasantness of presented sounds: absolute evaluation and pairwise comparison.

For the Pairwise Comparisons method, each sound is matched head-to-head with each of the other sounds. Each sound gets 1 point for a one-on-one win and a half a point for a tie. The sound with highest scoring is the most unpleasant. 12 sounds were presented to listeners in 66 pairs. The order of the pairs was in compliance with method proposed by Ross [1, 2].

In the absolute evaluation method, subjects were asked to evaluate the unpleasantness of the presented sound by moving a slider bar with a five indicated states; not at all unpleasant, little unpleasant, moderate unpleasant, very unpleasant and extremely unpleasant. Slider's thumb position assigns a value from 0 (not at all unpleasant) to 1000 (for extremely unpleasant) with an increment of 1. 36 sounds were presented to listeners in random order. The completed factorial experiment was created.

Stimuli

A sound recorded in an electric vehicle was used for these experiments. The car was a Citroen C-Zero (record provided by PSA). The driving condition was full throttle acceleration from 0 to 130 km/h on a chassis dyno. This corresponds to an engine speed from 0 to 7800 rpm. Bandstop filters were used to increase and decrease the amplitude of some prominent orders related to the electric motor and transmission. Likewise, inverter noise was used.

For the absolute evaluation experiment, as first factor of analysis, orders 1, 2 and 3 were modified. As second factor, the correction was made on the orders 48 and 56. Each sound is 22 seconds in length and corresponds to full acceleration from idle to 7800 rpm. Regarding the paired comparison test, as a first factor of analysis orders 8 and 10 were modified. As second factor, order 25 was altered. Time duration of sounds were decreased to 2.7 seconds. It corresponds to an acceleration from 1800 rpm to 3500 rpm. The third factor of analysis was the same for both experiments – inverter noise.

Additionally, highpass filter with cut off frequency of 50 Hz was applied to the original recording in order to remove prominent chassis dyno noise. Sounds were filtered using LEA v3.2.0 software. Table 1-A and 2-A display a list of prepared sounds with corresponding modifications.

Table 1-A. Prepared sounds with corresponding modifications for absolute evaluation.

No	File name	1, 2, 3 orders	48, 56 orders	Inverter
1	1-3_deamp_12_48_56_rem_inv_rem	-12	-6	-6
2	1-3_deamp_12_48_56_rem	-12	-6	0
3	1-3_deamp_12_48_56_rem_inv_amp_6	-12	-6	6
4	1-3_deamp_12_inv_rem	-12	0	-6
5	1-3_deamp_12	-12	0	0
6	1-3_deamp_12_inv_amp_6	-12	0	6
7	1-3_deamp_12_48_56_amp_6_inv_rem	-12	6	-6
8	1-3_deamp_12_48_56_amp_6	-12	6	0
9	1-3_deamp_12_inv_48_56_amp_6	-12	6	6
10	1-3_deamp_6_48_56_rem_inv_rem	-6	-6	-6
11	1-3_deamp_6_48_56_rem	-6	-6	0
12	1-3_deamp_6_48_56_rem_inv_amp_6	-6	-6	6
13	1-3_deamp_6_inv_rem	-6	0	-6
14	1-3_deamp_6	-6	0	0
15	1-3_deamp_6_inv_amp_6	-6	0	6
16	1-3_deamp_6_48_56_amp_6_inv_rem	-6	6	-6
17	1-3_deamp_6_48_56_amp_6	-6	6	0
18	1-3_deamp_6_inv_48_56_amp_6	-6	6	6
19	48_56_rem_inv_rem	0	-6	-6
20	48_56_rem	0	-6	0
21	48_56_rem_inv_amp_6	0	-6	6
22	inv_rem	0	0	-6
23	clean	0	0	0
24	inv_amp_6	0	0	6
25	48_56_amp_6_inv_rem	0	6	-6
26	48_56_amp_6	0	6	0
27	48_56_amp_6_inv_amp_6	0	6	6
28	1-3_amp_6_inv_48_56_rem	6	-6	-6
29	1-3_amp_6_48_56_rem	6	-6	0
30	1-3_amp_6_48_56_rem_inv_amp_6	6	-6	6
31	1-3_amp_6_inv_rem	6	0	-6
32	1-3_amp_6	6	0	0
33	1-3_amp_6_inv_amp_6	6	0	6
34	1-3_amp_6_inv_rem_48_56_amp_6	6	6	-6
35	1-3_amp_6_48_56_amp_6	6	6	0
36	1-3_amp_6_inv_48_56_amp_6	6	6	6

Table 2-A. Prepared sounds with corresponding modifications for paired comparison.

No	File name	8, 10 orders	25 order	Inverter
1	'8_10_deamp_10_inv_rem_16bit.wav'	-10	0	-10
2	'8_10_deamp_10_16bit.wav'	-10	0	0
3	'8_10_deamp_10_inv_amp_6_16bit.wav'	-10	0	6
4	'inv_rem_16bit.wav'	0	0	-10
5	'moreclean_16bit.wav'	0	0	0
6	'inv_amp_6_16bit.wav'	0	0	6
7	'25_amp_10_inv_rem_16bit.wav'	0	10	-10
8	'25_amp_10_16bit.wav'	0	10	0
9	'25_amp_10_inv_amp_6_16bit.wav'	0	10	6
10	'8_10_amp_10_inv_rem_16bit.wav'	10	0	-10
11	'8_10_amp_10_16bit.wav'	10	0	0
12	'8_10_amp_10_inv_amp_6_16bit.wav'	10	0	6

Subjects

Nineteen listeners (13 male and 6 female) took part in this study. They were mostly university students with no or little prior experience with this type of experiments. Candidates were mostly French native speakers, without any known hearing problems.

5A.3 Results and discussion

Paired comparison

Data were pooled over individuals, yielding a 12x12 cumulative paired-comparison matrix. The average preference scores were calculated by applying the linear model to the cumulative paired-comparison matrix. Figure 1-A depicts averaged preference scores for each sound included in table 2-A. Highest values on Y-axis indicate more unpleasant sounds. The difference between the unpleasantnesses perceived for each sound seems to be significant. A more exhaustive statistical analysis is presented in table 4-A.

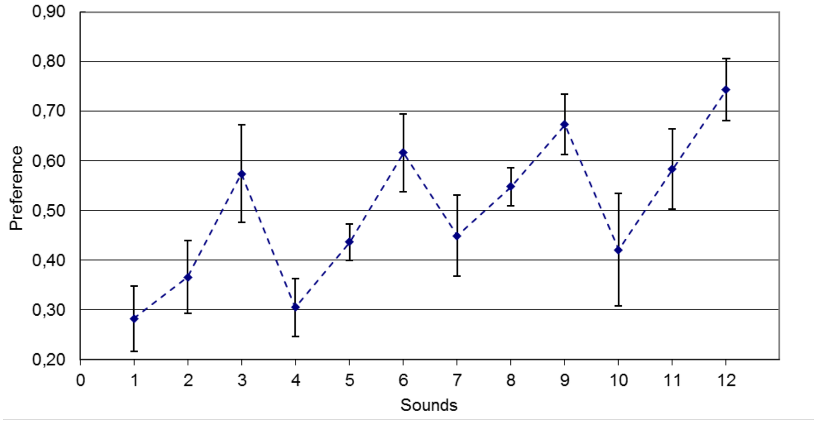

Fig. 1-A. Means for each stimulus. Vertical bars denote 0.95 confidence intervals

As it was describe before, the completed factorial experiment was not used for pairwise comparison method. For this reason, an ANOVA test was calculated separately for two factors. As a first combination, factors ‘orders 8 and 10’ and ‘Inverter’ were used kipping the factor ’25 order’ fixed (without modification). Table 3-A and figure 2-A depict calculated results. Afterwards, the same procedure was used with factors ’25 order’ and ‘Inverter’. In this case, factor ’8 and 10 order’ was fixed (without modification).

Table 3-A. Repeated Measures Analysis of Variance

	SS	df	MS	F	p
Intercept	39,56177	1	39,56177	11993,87	0,000000
Error	0,05937	18	0,00330		
8 and 10 order	0,93939	2	0,46969	10,42	0,000270
Error	1,62350	36	0,04510		
Inverter	2,74293	2	1,37147	25,78	0,000000
Error	1,91486	36	0,05319		
8, 10 order * inverter	0,03058	4	0,00764	0,99	0,420657
Error	0,55815	72	0,00775		

Table 3-A demonstrates that both factors are statistically significant. Nevertheless, the interactions effect results statistically nonsignificant. This result can be seen in figure 2-A. Green, red and blue lines depict the interaction of different levels for inverter

with different modification levels of low orders. Similar results were achieved for the factors ’25 order’ and ‘Inverter’. Despite the fact that influence of both factors are significant, this is not the case of the interaction effect.

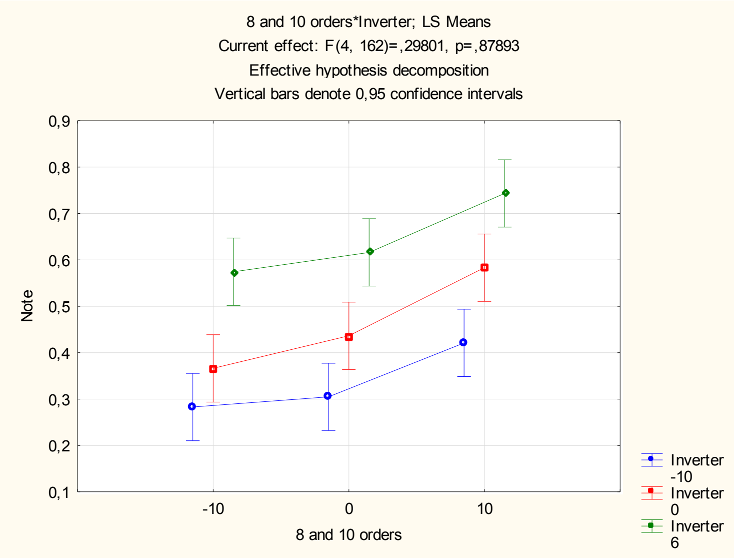

Fig. 2-A. Interaction between low orders and inverter

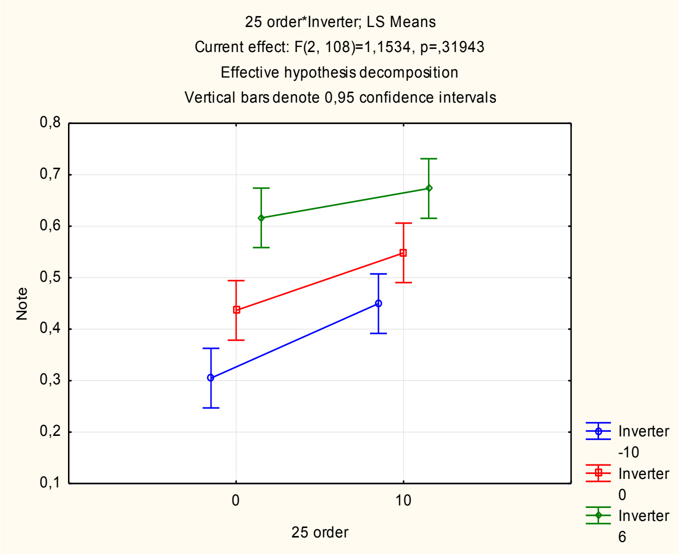

Fig. 3-A. Interaction between moderate orders and inverter

In order to thoroughly examining the statistically significant differences between sounds, a Tukey's test was conducted. Table 4-A yields the results. As can be observed, highest differences in unpleasantness judgments occurs to excerpts with different amplification of the inverter component. Amplifications of low and medium orders are also significant, but less than inverter. An amplification of 10 dB in low orders is perceived with the same unpleasant as without modification.

Overall unpleasantness judgments may be predicted by a combination of elementary sound characteristics, such as those captured by conventional psychoacoustic metrics. To explore the validity of this assumption for the present data set, a number of psychoacoustic indices were computed for all of the sounds. Particularly, the contribution of loudness and loudness level, sound pressure level, roughness, fluctuation strength, sharpness and tonalness (prominence ratio) to overall unpleasantness was investigated. The metrics are specified in table 5-A.

Applying a stepwise regression model to include or exclude predictors (psychoacoustic metrics), the A-weighted equivalent sound pressure level, the prominence ratio for 1,1 kHz (25 order) and for 7,1 kHz (inverter) were statistically significant. Tables 5-A and 6-A depict calculated values.

Table 4-A. Tukey's test for paired comparisons

	Sounds	1	2	3	4	5	6	7	8	9	10	11	12
1	-10/0/-10		0,879	0,000	1,000	0,084	0,000	0,038	0,000	0,000	0,188	0,000	0,000
2	-10/0/0	0,879		0,002	0,986	0,961	0,000	0,879	0,013	0,000	0,995	0,001	0,000
3	-10/0/6	0,000	0,002		0,000	0,188	1,000	0,329	1,000	0,703	0,084	1,000	0,033
4	0/0/-10	1,000	0,986	0,000		0,252	0,000	0,136	0,000	0,000	0,448	0,000	0,000
5	0/0/0	0,084	0,961	0,188	0,252		0,015	1,000	0,512	0,000	1,000	0,121	0,000
6	0/0/6	0,000	0,000	1,000	0,000	0,015		0,038	0,969	0,992	0,005	1,000	0,302
7	0/10/-10	0,038	0,879	0,329	0,136	1,000	0,038		0,703	0,000	1,000	0,229	0,000
8	0/10/0	0,000	0,013	1,000	0,000	0,512	0,969	0,703		0,329	0,302	1,000	0,005
9	0/10/6	0,000	0,000	0,703	0,000	0,000	0,992	0,000	0,329		0,000	0,813	0,961
10	10/0/-10	0,188	0,995	0,084	0,448	1,000	0,005	1,000	0,302	0,000		0,050	0,000
11	10/0/0	0,000	0,001	1,000	0,000	0,121	1,000	0,229	1,000	0,813	0,050		0,057
12	10/0/6	0,000	0,000	0,033	0,000	0,000	0,302	0,000	0,005	0,961	0,000	0,057	

Table 5-A. Psychoacoustic metrics of individual sounds

No.	1	2	3	4	5	6	7	8	9	10	11	12
8 and 10 orders value (dB)	-10	-10	-10	0	0	0	0	0	0	10	10	10
25 order value (dB)	0	0	0	0	0	0	10	10	10	0	0	0
inverter value (dB)	-10	0	6	-10	0	6	-10	0	6	0	-10	6
Leq dB(A)	49,6	49,6	49,6	50,5	50,5	50,5	52,1	52,1	52,1	54,8	54,8	54,8
Max dB(A)	52,4	52,4	52,4	54,2	54,2	54,2	56,4	56,4	56,4	61,2	61,2	61,2
Spectral Gravity Cen. (Hz)	380	374	380	370	372	377	432	433	438	363	362	365
Max loudness (Sone)	8,9	8,8	8,9	9,2	9,3	9,4	9,9	9,9	10,0	11,5	11,5	11,6
Max loudness (Phone)	71,5	71,3	71,5	72,1	72,2	72,3	73,1	73,1	73,2	75,3	75,2	75,3
Max Sharpness (Acum)	1,3	1,2	1,3	1,1	1,2	1,3	1,1	1,2	1,3	1,1	1,1	1,2
N5 (Sones)	8,6	8,5	8,6	9,0	9,1	9,2	9,6	9,6	9,7	11,0	10,9	11,1
L5 (Phons)	71,1	70,8	71,1	71,8	71,8	71,9	72,6	72,7	72,8	74,5	74,5	74,7
N10 (Sones)	8,4	8,3	8,4	8,8	8,9	9,0	9,2	9,3	9,4	10,6	10,6	10,7
L10 (Phons)	70,7	70,5	70,7	71,4	71,5	71,6	72,1	72,1	72,3	74,1	74,0	74,2
Prominence ratio 350 Hz (dB)	0	0	0	2,8	2,8	2,8	2,8	2,8	2,8	7,1	7,1	7,1
Prominence ratio 1,1 kHz (dB)	2,3	2,3	2,3	2,3	2,3	2,3	4,7	4,7	4,7	2,3	2,3	2,3
Prominence ratio 7,1 kHz (dB)	0	1,6	4,5	0	1,6	4,5	0	1,6	4,5	1,6	0	4,5

Table 6-A. Univariate Tests of Significance, Effect Sizes, and Powers for score

	SS	df	MS	F	p	Partial eta-squared	Non-centrality	Observed power
Laeq (dB A)	0,049	1,000	0,049	70,125	0,000	0,898	70,125	1,000
Prominence ratio 7,1 kHz (dB)	0,166	1,000	0,166	236,988	0,000	0,967	236,988	1,000
Prominence ratio 1,1 kHz (dB)	0,009	1,000	0,009	12,275	0,008	0,605	12,275	0,865

In compliance with expectations, a prominence ratio is a significant predictor. However, it varies over frequency. For low orders (350 Hz), despite the fact that prominence ratio reaches the highest value (up to 7.1 dB) it doesn't show any differences in terms of overall impression of unpleasantness. For medium frequencies (1,1 kHz), amplification of 10 dB provides a significant difference but lower than for inverter amplification. It means that modification of high frequency components is crucial in terms of human perception of unpleasantness. The same prominence ratio value for 7.1 kHz is much more unpleasant than for 1.1 kHz. On the other hand, as is shown in figure 3-A, there is no interaction between these two factors. Thus, when high frequency noise is prominent, amplification or attenuation of other orders has no influence over listener judgments.

Absolute evaluation

Figure 4-A depicts averaged preference scores obtained for each sound by absolute evaluation test (order of sounds as table 1-A). Highest values on Y-axis indicate more unpleasant sounds. Because of higher scattering in listeners responses confidence intervals are higher comparing with the paired comparison method. In order to determine the existence of a significant difference, an ANOVA test was performed. As a completed factorial experiment was design, ANOVA was calculated for all factors. Results are depicted in table 7-A and figure 5-A. R1 denotes factor '1-3 orders', R2 '58-56 orders' and R3 – inverter. As can be seen only R1 and R2 are statistically significant as well as interactions effect between them (p-value < 0,05). These two factors were used as input for a post-hoc test. Table 8-A displays results from Tukey test for R1 and R2.

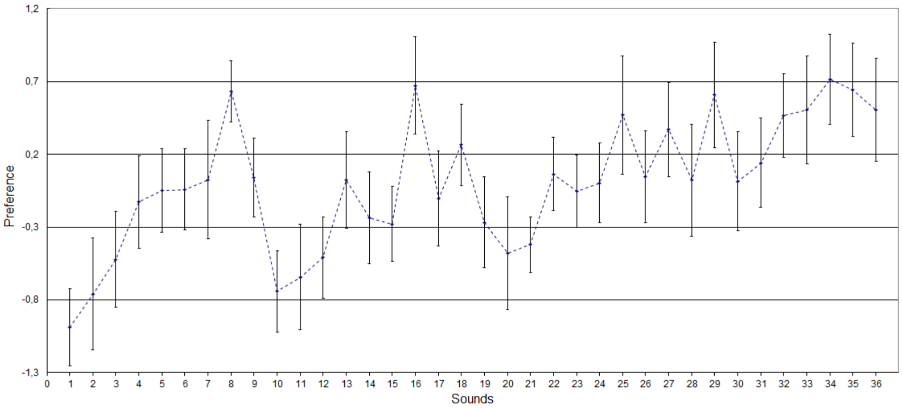

Fig. 4-A. Means for each stimulus. Vertical bars denote 0.95 confidence intervals

Table 7-A. Repeated Measures Analysis of Variance for absolute evaluation

	SS	df	MS	F	p
Intercept	154418713	1	154418713	272,4284	0,000000
Error	10202815	18	566823		
R1	819195	3	273065	4,4287	0,007433
Error	3329502	54	61657		
R2	1673647	2	836823	10,1794	0,000313
Error	2959466	36	82207		
R3	5745	2	2873	0,1264	0,881658
Error	818173	36	22727		
R1*R2	616091	6	102682	5,3996	0,000065
Error	2053797	108	19017		
R1*R3	282927	6	47155	1,5943	0,155680
Error	3194234	108	29576		
R2*R3	183730	4	45933	1,9634	0,109263
Error	1684387	72	23394		
R1*R2*R3	312819	12	26068	1,2327	0,261956
Error	4567694	216	21147		

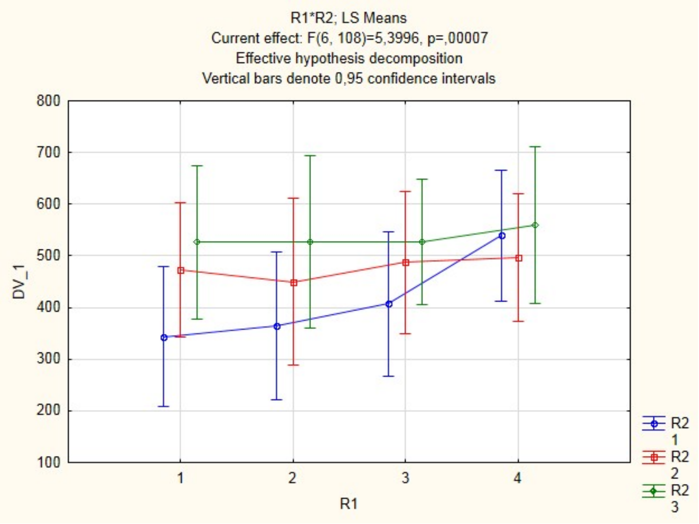

Fig. 1-A. Interaction between the first and the second factor

Table 8-A. Tukey HSD test

No.	R1 (dB)	R2 (dB)	1	2	3	4	5	6	7	8	9	10	11	12
1	-12	-6		0,000	0,000	1,000	0,005	0,000	0,370	0,000	0,000	0,000	0,000	0,000
2	-12	0	0,000		0,648	0,003	0,999	0,635	0,336	1,000	0,619	0,310	0,998	0,048
3	-12	6	0,000	0,648		0,000	0,134	1,000	0,001	0,932	1,000	1,000	0,993	0,979
4	-6	-6	1,000	0,003	0,000		0,058	0,000	0,880	0,001	0,000	0,000	0,000	0,000
5	-6	0	0,005	0,999	0,134	0,058		0,128	0,896	0,951	0,121	0,035	0,788	0,003
6	-6	6	0,000	0,635	1,000	0,000	0,128		0,001	0,927	1,000	1,000	0,992	0,981
7	0	-6	0,370	0,336	0,001	0,880	0,896	0,001		0,102	0,001	0,000	0,034	0,000
8	0	0	0,000	1,000	0,932	0,001	0,951	0,927	0,102		0,920	0,678	1,000	0,191
9	0	6	0,000	0,619	1,000	0,000	0,121	1,000	0,001	0,920		1,000	0,991	0,983
10	6	-6	0,000	0,310	1,000	0,000	0,035	1,000	0,000	0,678	1,000		0,897	1,000
11	6	0	0,000	0,998	0,993	0,000	0,788	0,992	0,034	1,000	0,991	0,897		0,408
12	6	6	0,000	0,048	0,979	0,000	0,003	0,981	0,000	0,191	0,983	1,000	0,408	

Likewise in paired comparison experiment, a number of psychoacoustic parameters were computed for all of the sounds. The metrics are specified in table 9-A. Applying a stepwise regression model to include or exclude predictors, 10% percentile loudness level and 10% percentile loudness, together with prominence ratio for 150 Hz are statistically significant. Table 10-A depicts calculated values.

From post-hoc test we know that modification of orders 48 and 56 is significant. Prominence ratio for 5.8 kHz does not act as a good metric predictor. Nevertheless, discussed orders are audible mostly during last seconds of the sounds and this might affect overall unpleasantness judgments. Unlike previous experiment, prominence ratio for low frequencies correlates with listener judgments. In fact, modification of low orders is clearly audible, but causes increased value of percentile loudness. In summary, all significant predictors used in this study describe the same modifications – orders 1 to 3.

Table 9-A. Psychoacoustic metrics of individual sounds

No.	1-3 orders value (dB)	48_56 orders value (dB)	Inverter value (dB)	prominence 7,1 kHz (dB)	prominence 5,8 kHz (dB)	prominence 150 Hz (dB)	Laeq dB(A)	Max Laeq (dB)	SGC (Hz)	Max loudness (Sone)	Max loudness (Phone)	Max Sharpness (Acum)	N5 (Sones)	L5 (Phons)	N10 (Sones)	L10 (Phons)
1	-12	-6	-6	0	0	4	57,7	62,5	451	16,2	80,2	1,4	15,1	79,2	14,8	78,8
2	-12	-6	0	0	0	4	57,7	62,5	451	16,2	80,2	1,4	15,1	79,2	14,8	78,9
3	-12	-6	6	0	0	4	57,7	62,5	453	16,2	80,2	1,4	15,2	79,2	14,8	78,9
4	-12	0	-6	0	0	4	57,7	62,5	455	16,3	80,3	1,5	15,4	79,4	15,0	79,1
5	-12	0	0	0	0	4	57,7	62,5	456	16,3	80,3	1,5	15,4	79,4	15,0	79,1
6	-12	0	6	0	0	4	57,7	62,5	458	16,3	80,3	1,5	15,4	79,5	15,0	79,1
7	-12	6	-6	0	0,5	4	57,8	62,5	470	16,7	80,6	1,6	15,7	79,8	15,3	79,3
8	-12	6	0	0	0,5	4	57,8	62,5	470	16,7	80,6	1,6	15,7	79,8	15,3	79,4
9	-12	6	6	0	0,5	4	57,8	62,5	472	16,7	80,6	1,6	15,7	79,8	15,3	79,4
10	-6	-6	-6	0	0	4,9	57,8	62,7	401	16,8	80,7	1,3	15,4	79,5	15,0	79,1
11	-6	-6	0	0	0	4,9	57,8	62,7	401	16,8	80,7	1,3	15,4	79,5	15,0	79,1
12	-6	-6	6	0	0	4,9	57,8	62,7	403	16,8	80,7	1,4	15,5	79,5	15,1	79,1
13	-6	0	-6	0	0	4,9	57,9	62,7	405	16,8	80,7	1,5	15,7	79,7	15,3	79,3
14	-6	0	0	0	0	4,9	57,9	62,7	406	16,8	80,7	1,5	15,7	79,7	15,3	79,3
15	-6	0	6	0	0	4,9	57,9	62,7	407	16,8	80,7	1,5	15,7	79,7	15,3	79,3
16	-6	6	-6	0	0,5	4,9	57,9	62,7	417	17,0	80,9	1,6	16,1	80,1	15,6	79,6
17	-6	6	0	0	0,5	4,9	57,9	62,7	418	17,0	80,9	1,6	16,1	80,1	15,6	79,6
18	-6	6	6	0	0,5	4,9	57,9	62,7	419	17,0	80,9	1,6	16,1	80,1	15,6	79,6
19	0	-6	-6	0	0	7	58,3	63,5	301	18,2	81,8	1,3	16,3	80,3	15,7	79,7
20	0	-6	0	0	0	7	58,3	63,5	301	18,2	81,8	1,3	16,3	80,3	15,7	79,7
21	0	-6	6	0	0	7	58,3	63,5	302	18,2	81,9	1,3	16,3	80,3	15,8	79,8
22	0	0	-6	0	0	7	58,3	63,5	304	18,2	81,8	1,4	16,5	80,5	16,0	80,0
23	0	0	0	0	0	7	58,3	63,5	304	18,2	81,8	1,4	16,5	80,5	16,0	80,0
24	0	0	6	0	0	7	58,3	63,5	305	18,2	81,9	1,4	16,6	80,5	16,0	80,0
25	0	6	-6	0	0,5	7	58,3	63,5	308	18,0	81,8	1,5	16,8	80,7	16,3	80,3
26	0	6	0	0	0,5	7	58,3	63,5	312	18,2	81,9	1,6	16,9	80,8	16,4	80,3
27	0	6	6	0	0,5	7	58,3	63,5	315	18,3	82,0	1,6	16,9	80,7	16,4	80,4
28	6	-6	-6	0	0	10	59,6	66,5	202	21,4	84,2	1,3	18,4	82,0	17,4	81,2
29	6	-6	0	0	0	10	59,6	66,5	202	21,4	84,2	1,3	18,4	82,0	17,4	81,2
30	6	-6	6	0	0	10	59,6	66,5	203	21,5	84,2	1,3	18,4	82,1	17,4	81,2
31	6	0	-6	0	0	10	59,6	66,5	203	21,4	84,2	1,3	18,6	82,2	17,6	81,4
32	6	0	0	0	0	10	59,6	66,5	203	21,4	84,2	1,3	18,6	82,2	17,6	81,4
33	6	0	6	0	0	10	59,6	66,5	204	21,5	84,2	1,3	18,6	82,2	17,6	81,4
34	6	6	-6	0	0,5	10	59,6	66,5	206	21,4	84,2	1,5	18,9	82,4	18,1	81,8
35	6	6	0	0	0,5	10	59,6	66,5	206	21,4	84,2	1,5	18,9	82,4	18,1	81,8
36	6	6	6	0	0,5	10	59,6	66,5	207	21,5	84,2	1,5	18,9	82,4	18,1	81,8

Table 10-A. Summary of Stepwise Regression

	Step (+in/-out)	Multiple (R)	Multiple (R-square)	R-square (change)	F - to (entr/rem)	p-value	Variables (included)
L10 (Phons)	1	0,69	0,47	0,47	27,68	0,00	1
Prominence ratio 150 Hz	2	0,87	0,75	0,28	32,95	0,00	2
N10 (Sones)	3	0,89	0,79	0,05	6,41	0,02	3

5A.4 Conclusion

Considering electric cars, unpleasantness for in-vehicle auditory may be partially predicted by conventional psychoacoustic metrics. This study shows how for quieter sounds, A-weighted equivalent sound pressure level is a meaningful predictor of unpleasantness. However, in-vehicle noises with the same value of Laeq can be perceived differently when they have prominent tones in mid and high frequency range. Therefore, prominence ratio values necessarily should be included in unpleasantness predictions.

The second experiment leads to partially similar conclusion. Unpleasantness correlates with 10% percentile loudness and loudness level. In sense of describing total energy of the signal, theses parameters can be identified with Laeq from previous experiment. The statistical analysis showed that prominence ratio for middle and high frequencies is not a significant predictor. On the other hand, factor R2, which directly corresponds to prominence of 5.8 kHz tone, is statistically significant. This result is due to the tone is audible mostly during the last seconds of a sound and therefore, prominence ratio shows low values.

The differences obtained between the two methods might be caused by the fact that sounds used in absolute evaluation test are too long and present a high variation over time. Inverter contribution to overall impression of unpleasantness was nonsignificant for absolute evaluation experiment. Inverter noise is clearly noticeable at low and medium rpm range and thus, at the beginning of the sound. Listeners can “forget” the beginning of a sample and judge it by its end. A similar phenomenon can by noticed for high frequency orders (48 and 56). Although it can be considered as an important factor, any sensible metric can be found to predict its behaviour.

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Annex 5B
Warning Sounds for Electric Vehicles

[1]Parizet, Etienne; [1]Robart, Ryan; [2]Ellermeier, Wolfgang; [3]Janssens, Karl*;
[3]Bianciardi, Fabio; [4]Haider, Manfred; [5]Quinn, David; [6]Chamard, Jean-Christophe

[1]LVA, INSA-Lyon, Villeurbanne, France
[2]TUD, Darmstadt, Germany
[3]Siemens Industry Software NV, Leuven, Belgium
[4]AIT, Wien, Austria
[5]Nissan, Sunderland, United Kingdom
[6]PSA Peugeot-Citroën, Vélizy, France

Abstract. Electric vehicles (or hybrid ones) are very silent at low speeds (below 30 km/h) and can be dangerous for pedestrian, especially vulnerable ones as visually impaired people. The European founded project eVADER aims at developing a prototype vehicle including an automatic pedestrian detection device and an array of speakers focusing a warning sound in the direction of the pedestrian. The warning sound should be optimized too, in order to be easily detectable while not too loud. Research is conducted in order to investigate the influence of some timbre parameters on the detectability and annoyance of warning sounds.

Different warning sounds were synthesized according to a fractional factorial design. Factors were related to three basic timbre parameters. Two laboratory experiments took place. The first one focused on detectability. The task of the listener was to detect an approaching car (20 km/h) as soon as possible. The second experiment was devoted to the unpleasantness of warning sounds. Stimuli were presented to listeners who had to evaluate their unpleasantness on a continuous scale.

The tests have shown that some warning sounds can make an electric vehicle as detectable as a diesel car, for a much lower sound level. However, most warning sounds also tend to increase the unpleasantness of the car sound. Nevertheless, some signals seem to provide a good compromise between the two objectives.

5B.1 Introduction

Electric and hybrid vehicles are very quiet at low speeds (typically below 30 km/h). The level of the noise emitted by such vehicles is 5 to 7 dB(A) lower than the one of conventional Diesel cars. This is very beneficial to people living in an urban area, because transportation noise is a major source of annoyance in cities. On the other hand, this represents a hazard for pedestrian, who may not hear an approaching car. Vulnerable people as visually-impaired ones have a very strong concern about such cars and manufacturers use additional warning sounds in order to prevent this risk. Though several studies have already been conducted in that field (e.g. (1), (2)), the easiest way to solve this safety issue is to use loud warning sounds, which cancels the noise reduction advantage of electric cars. Regulations, either already decided (NHTSA) or under preparation (in Europe), go this way. As an example, the regulation currently prepared in Europe states that "the (warning) sound level may not exceed the sound level of a similar internal combustion engine vehicle". It should be possible to use more efficient warning sounds.

The eVADER project brings together partners from universities, research centers, car manufacturers and a supplier. Last but not least, the European Blind Union (EBU) is a partner, so that end users are represented in the consortium. The goal of this project is to develop a prototype vehicle combining a high safety for pedestrian and a low noise annoyance for city residents. Several technical solutions are developed:

- An automatic pedestrian detection device;
- A set of loudspeakers focusing the sound in the direction of the detected pedestrian;
- A warning sound designed so that it can be detected in an urban environment at a low level.

This paper will describe studies focusing on this third objective. It will present two listening test experiments: one aimed at evaluating the influence of some timbre parameters on the detectability, and one aimed at assessing the annoyance of warning sounds. The two experiments were conducted by various partners of the project, which allowed to use large subjects samples.

5B.2 Detectability

The first part of the study was related to the detectability of warning sounds. The main question was the following: “given the background traffic noise of an urban environment, is it possible to make a warning sound easily detectable in spite of a low level?” It was decided to limit the study to multi-tone sounds, in a middle frequency range (300 - 1500 Hz). The lowest frequency was chosen in view of the technical limitation of the loudspeakers to be used in the prototype; for a high radiation efficiency at low frequencies, very large speakers would have been necessary. The high frequency limit was set because people suffering from presbyacousis have high hearing thresholds at higher frequencies.

Procedure

In this experiment, three timbre factors were investigated: the number of tones, the frequency variation and the temporal variation. Each factor could have three levels: as an example, the number of tones could be 3, 6 or 9. A fractional factorial design was used, so that 9 combinations were used (instead of 27 in a full factorial design). More details about the stimuli definition can be found in (3).

Therefore, 9 stimuli were synthesized; they all had the same A-weighted level. Then they were modified in order to represent a moving source, passing in front of a listener at the speed of 20 km/h. Finally, each modified stimulus was added to the recording of an electric vehicle recorded at 20 km/h by a dummy head located close to the road. This way, it was possible to simulate the situation of a pedestrian facing the road, waiting to cross this road and paying attention to any approaching car (figure 1-B).

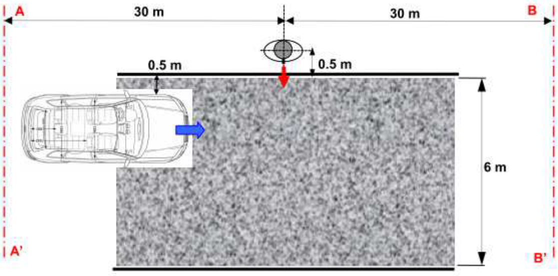

Fig. 1-B. "Waiting to cross" scenario

The recording of the electric vehicle alone as well as the one of a similar diesel car were added to this set of stimuli. The level of warning sounds were adjusted so that they increase the level of the electric vehicle only slightly (less than 2 dB(A) , see figure 2-B). The level of the diesel car was more than 5 dB(A) higher.

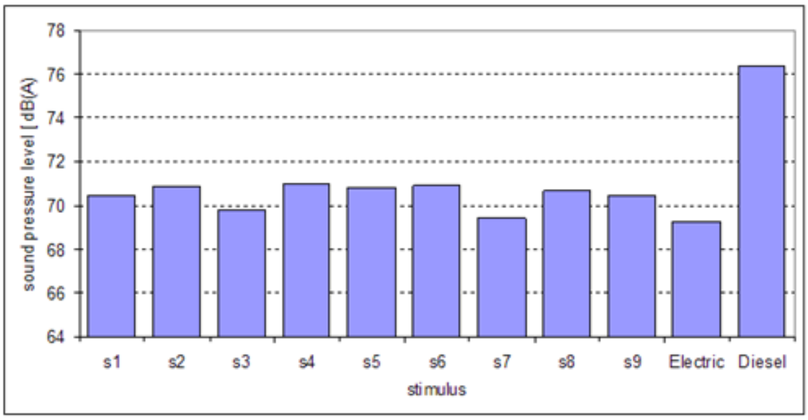

Fig. 2-B. Peak level (A-weighted SPL) of each stimulus used in experiment 1

During the experiment, the listener was hearing a background traffic noise through headphones. Rain noise was added, as this represents a very difficult situation for blind pedestrian. The level of this noise was 69 dB(A). At randomly selected times, one of the car stimuli was added to the noise. This car could arrive from the left or from the right of the listener. The task of the listener was to detect the approaching car as soon as possible and its direction. He gave his answer by pressing a key of a computer keyboard. Two keys were used: the <Enter> key in the case of a "right" answer, and the <Space> bar for the "left" answer. The response time (from the starting of the stimulus) was measured and stored by the computer.

Each sound was presented 8 times (4 times from each direction) so that a listener was presented 88 stimuli (in a random order) in total. 110 subjects participated to the experiment; among them, 33 were visually-impaired people.

Results

The averaged response time was converted to distance from the listener at detection. These distances are shown in figure 3-B. The red area in figure 3-B represents the “risk area”. If the pedestrian starts crossing the road while the car is closer than 5 meters away, he may be hit by the car, given the averaged reaction time needed by the driver to start breaking (e.g (4)). The electric vehicle is detected in this area, which confirms that EV can be dangerous for pedestrian (e.g. (5)).

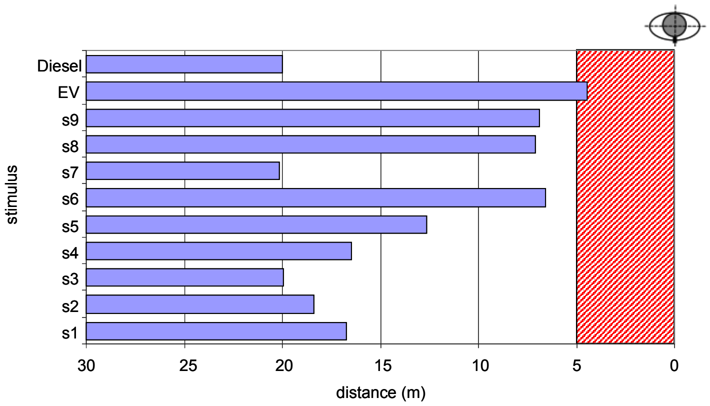

Fig. 2-B. Avg. distance from the listener at detection. The red area represents the "risk area"

Warning sounds had quite different efficiencies, depending on their timbre. Some warning sounds are nearly inefficient (s6, s8 and s9). Some other ones make the EV as easy to detect as the diesel car (s3 and s7). And figure 2-B clearly shows that such differences are not related to the level of these sounds - timbre features are the only reason for such differences. Further analysis showed that some controlled features were favorable to detection:

- A low number of tones: the overall sound level was kept constant, so that the difference between each tone level and its detection threshold was greater when the number of tones was low.
- Amplitude modulation: fluctuations in amplitude help the listener to detect the signal in the background of traffic noise.

5B.3 Unpleasantness

The second part of the study was related to the unpleasantness of the warning sounds. The listener was asked to evaluate their unpleasantness, imagining to stand in the street, facing the road, listening to the cars passing by at 20 km/h.

Procedure

The experiment was devoted to the evaluation of the unpleasantness of 20 warning sounds: 11 stimuli were the same as in experiment 1, and 9 stimuli were added representing an EV at 20 km/h with a warning sound characterized by different levels of the three components of the sound determined as favorable characteristics for detection in the previous experiment. The experiment was conducted in two conditions: some listeners were presented the stimuli without any background noise and for some other ones, a low-level traffic noise (57 dBA) was added to each stimulus. In both cases, the task of the listener was to evaluate the unpleasantness of the sound. He gave his answer by moving a cursor on a continuous scale, labeled from "not at all unpleasant" to "extremely unpleasant". The position of the cursor was stored as a number between 0 (for "not at all unpleasant") to 1000 ("extremely unpleasant"). Each sound was presented twice, the order of presentation being randomly selected. 145 subjects participated to this last experiment, which was conducted in four laboratories.

Results

The repeatability of each listener was evaluated by computing a mean squared difference between the two values he gave for each sound, namely:

$$C = \sqrt{\frac{1}{20}\sum_{n=1}^{20}\left(x_{n1} - x_{n2}\right)^2} \qquad \text{Eq. 1-B}$$

where x_{n1} and x_{n2} represent the two evaluations of sound n. Individual coefficients range between 50 and 450 (mean value: 179, standard deviation: 65). For 23 subjects, this coefficient is higher than 250, which represents a full category of the scale: such subjects can be considered as inconsistent. Such a high number of inconsistent subjects means that the task was difficult. So it was decided to select most reliable subjects for further analysis. The maximum value for C was fixed to 150, which allowed selecting 56 people. 26 of them did the experiment with the background traffic noise and 30 without this noise.

An analysis of variance was done (repeated measures, background noise condition as an inter-individual factor and stimuli as intra-individual ones). The stimuli was the only influential factor [F(19, 988) = 48.5, $p<0.0001$]. The unpleasantness of each sound was averaged over this subpanel; results are shown in figure 4-B.

Homogeneous groups of sounds are represented by thick horizontal lines (these groups have been determined using Scheffe's technique).

As it can be seen on figure 4-B, most warning signals strongly increase the unpleasantness of the sound. This can be due to the fact that people felt very unfamiliar with such warning sounds. Three of them can be considered as equally unpleasant as the diesel car. The particularity of these sounds is that no temporal fluctuation was applied to their amplitude. Amplitude fluctuation increased unpleasantness; the first experiment had shown that it also increased the detectability of sounds.

In summary, figure 5-B gives an overview of the results combining the detectability and annoyance experiments. Only the same 11 sounds used in both experiments are presented. This figure shows that, for warning signals, unpleasantness increases with the efficiency of the sound. This is in line with some previously published results about warning sounds. The relation between efficiency and unpleasantness has already been proved for other kinds of warning sounds (e.g. (6), (7) and (8)).

But, if results are considered more precisely, some differences between sounds can be noted. For example, s1 and s15 are equally unpleasant, but s1 is easier to detect. On the other hand, s1 and s7 have similar performances as regard to detection, but s1 is much less unpleasant than s7.

As a result of this set of experiments, s1 (3 number of tones, no temporal and no frequency fluctuation) seems to be a good candidate as warning sound.

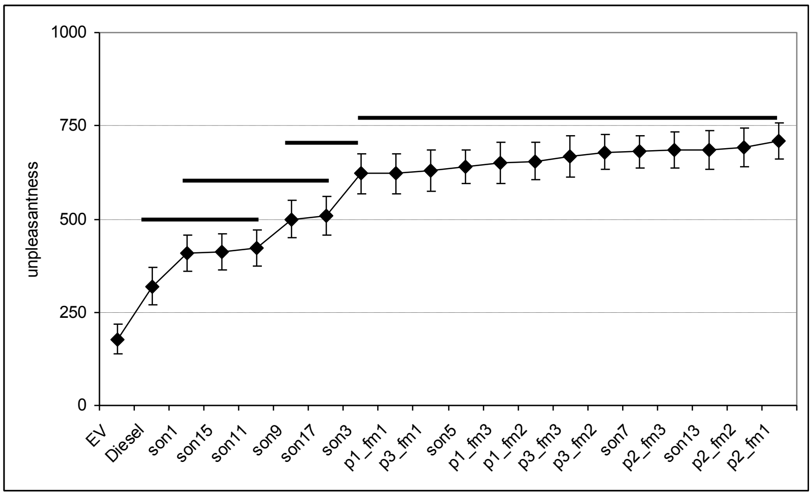

Fig. 4-B. Unpleasantness of each sound

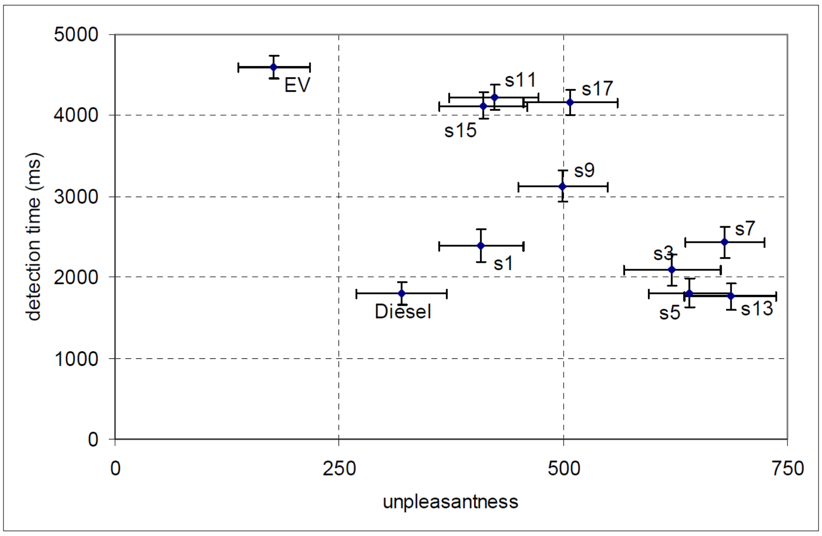

Fig. 5-B. Comparison of results from detection and unpleasantness experiments

5B.4 Conclusions

This paper presented two experiments aiming at evaluating the influence of basic timbre parameters of a warning signal on its detectability and annoyance. It has been shown that some warning sounds can make an electric vehicle as detectable as a diesel car, for a much lower sound level. Nevertheless, people reported these signals to increase the unpleasantness of the car sound. It is hypothesized that this was due to the unnaturalness of such signals and to their novelty. Further studies during which subjects could get used to such sounds would be useful. Nevertheless, some signals seem to provide a good compromise between the two objectives.

Finally, it should be recalled that the goal of these studies was not to define a warning signal for a typical application, but to investigate the influence of timbre parameters. This way, it is expected that car manufacturers will have some guidelines when defining their own signal, which should also fulfill some brand image requirements.

Aknowledgement

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Annex 5C

Detectability of Warning Sounds for Electric Vehicles at 30 km/h

Poveda-Martínez, Pedro[1], Peral-Orts, Ramón[2], Campillo-Davo, Nuria[2], Ramis-Soriano, Jaime[1]

[1]Applied Acoustics Group, University of Alicante. Crrta. San Vicente del Raspeig s/n. 03690 San Vicente del Raspeig, Alicante, Spain, pedro.poveda@ua.es

[2]Mechanical Engineering and Energy Department, Miguel Hernández University of Elche, Av de la Universidad, s/n. 03202 Elche, Spain, ramon.peral@umh.es

Abstract. Electric and hybrid Electric vehicles (EVs and HEVs) seem to be the future of transport in smart cities and the key for the total reduction of noise disturbance and pollution in urban areas. However, several problems have to be solved in order to guarantee the safety of these types of vehicles. So far, the use of HEVs has shown the danger of a “quiet” transport system in urban environments. This phenomenon occurs specially at low speed regimens, where the propulsion system noise overcomes the noise produced by aerodynamics and road/tired contact. Many papers about detectability of warning sounds for electric vehicles have been published. However, most of them are focused on a speed of 20 km/h. The vast majority of the European legislation establishes a maximum speed limit of 30 km/h in urban areas.

This paper analyses the detectability of warning sound a 30 km/h. For that, a group of listeners were polled. The subjects should detect the presence of a vehicle in a pass-by mode test. The study was made by means of an acoustic simulation with the help of a software tool. The results underscore the risk posed by electric vehicles even at the speed of 30 km/h. At the same time, the study reveals the importance of a good design for an effective warning sound.

5C.1 Introduction

Electric and Hybrid Electric Vehicles (EV and HEV) are proposed as a solution to reduce gas emission in cities, guaranteeing a good air quality in urban areas and to spare the non-renewable energy resources. Since HEV do not have the range limitations of Full EV and also not the drawback of emissions like the pure Internal Combustion Engine (ICE) vehicles, they are closer to the consumer’s expectations and the current driving patterns. In fact, worldwide demand for HEVs will advance rapidly from 1.6 million units in 2010 to 4.3 in 2015, and it is expected nearly 8 million by 2020 [1]. In this context there is an increasing awareness around the issue of the environmental noise. The World Health Organisation is reporting that traffic noise causes every year the loss of at least one million healthy life-years in Europe and it is responsible for over 20.000 deaths each year via resulting heart problems, reduced sleep quality, etc. The road industry alone cannot entirely solve this problem: road users, public authorities, automotive constructors have their role to play as well.

Therefore, real and tangible effects in noise reduction could only be achieved by a common effort and a shared responsibility of all these actors.

On the other hand the very low noise levels due to an approaching EV or HEV could be a danger to pedestrians and cyclists, especially for a particular sensitive population as elder and blind people. Thanks to the tyre/road noise, EV may generate a sufficient noise level to warn pedestrians under some driving conditions. Nevertheless, this level can be reduced under other circumstances, particularly when the speed decreases. In this case, they are more likely to mix with pedestrian traffic. Several research laboratories and main automotive manufacturers are developing external noise generators for such vehicles but some outstanding issues remain there. The first issue is how a significant warning level can be generated in front of the vehicle, without generating important environmental noise pollution by radiating high noise levels from the sides and rear of the vehicle. The second issue is concerned with the best feature of the warning noise to use. This should be perceived to come from a vehicle but not as alarming that it will cause a startle reaction and thus increase the danger. Finally, the warning sound (WS) need to change depending on the background noise surrounding the vehicle, however it is not clear how it and under which conditions.

The presence of EV affect the road safety specially at low speed regimens, where the propulsion system noise overcomes the noise produced by aerodynamics and road/tired contact. Many papers about detectability of warning sounds for electric vehicles have been published. However, most of them are focused on a speed of 20 km/h [2, 3, 4, 5]. However, Tte vast majority of the European legislation establishes a maximum speed limit of 30 km/h in urban areas.

In order to contribute to the study of the warning sound systems, the University of Alicante and the University Miguel Hernandez, have been carrying out a research project funded by Directorate General of Traffic (DGT). The aim of this project is to study the behaviour of some warning sounds at speed of 30 km/h.

5C.2 Materials and Methods

Warning Sounds

Research laboratories and the main automotive manufactures are proposed several types of warning sounds. These sounds aimed to increase the detectability of EV and HEV without becoming new annoying sound sources [2, 3, 4].

In order to establish a set of warning sounds, an exhaustive search was conducted to obtain public audio files. A total of 25 warning sounds were analysed, selecting those whose spectral content showed no relevant variations in time. Each audio file was first normalized in order to allow comparison between them.

Each sound focuses on a different frequency bandwidth, being all of them below 2 kHz. Warning sounds 1 to 5 correspond to broadband sounds while 6, 7 and 8 [4] represent tonal compositions with and without modulation.

Detectability of EVs/HEVs Protocol.

Psychoacoustic tests will be performed to determine the detectability of classified warning sounds in an urban environment. For that, a real situation has been recreated according to [4]: a pedestrian standing on the sidewalk, at a distance of 3 meters from the centre of the traffic lane, prepared to cross the road. Throughout the essay, different vehicle sounds, with and without AVAS, will be presented to the listener, simulating the movement in both directions. The vehicles will approach the listener individually, at a constant speed of aprox. 30 km/h, covering a distance of ±30 meters form the pedestrian. In order to increase the realism of the simulation, the vehicles will be presented together with an urban environment background noise. The subject must indicate, by pressing a button, the moment he perceives the vehicle approach.

Vehicle Sound samples were acquired from a pass-by test. A Head Acoustic HSM III dummy head was used with a sample frequency of 44100 Hz. The dummy head was situated at 3 meters from the centre of the traffic lane. The sound acquisition was made from ±30 meters from the dummy head. The measurements took place at the University Miguel Hernández of Elche, on a traffic lane with an asphalt characterization G20 + S20. The vehicle used was a Hybrid Toyota Pryus.

Warning Sounds were incorporated by means of signal processing. For that, each selected WS were processed to simulate a pass-by movement at a constant speed. A HRTF databased [6] was used to introduce the pedestrian head effect. The addition of warning sounds to the EV sound samples does not increase the peak level more than 3 dB(A) and never exceed the diesel car level.

As background noise, a sound samples recorded at a 2 lane road was used. The equivalent sound pressure level was 66.5 dB(A).

A software tool were implemented to perform the detectability test. The application emits, over a constant background noise, different sound samples, individually and randomly. Time between sound events varies between 1 and 20 seconds [4]. Each sound is played four times (two in the left-right direction and two in right-left direction) making a total of 40 sound events by subject. The user must indicate the approach of a vehicle by pressing a key.

5C.3 Results

A total of 47 subjects were polled (27 years old mean). The results show that electric vehicles require a longer response to be perceived. The vehicles is detected closer to pedestrians. The difference between the detectability of electric and hybrid vehicles is nearly 7 meters.

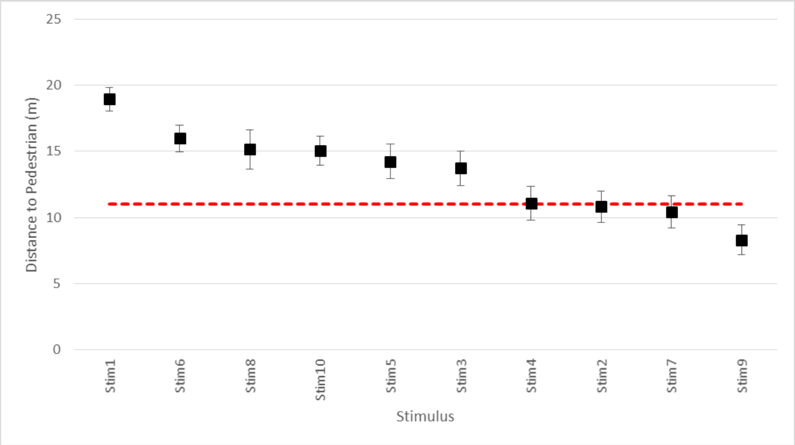

Fig. 1-C. Detectability results. Distance to pedestrian. Vertical bars denote 95% confidence intervals.

Red line denotes the vehicle stopping distance at 30 km/h and hence defines the safety zone. The use of warning sounds significantly increases the vehicle detectability. At the same time, the results underscores the risk of EV for pedestrian safety at speeds close to 30 km/h. According to Pearson correlation coefficient, no linear relation was appreciated between the detectability of the vehicle and the peak level.

5C.4 Conclusions

The results reveal a significant difference between the detectability of EV and ICV at 30 km/h. The incorporation of this kind of vehicles to the urban traffic supposes a real risk for pedestrians.

The use of warning sounds, especially in urban areas with low speed, can improve considerably the vehicle detectability and thereby, decrease the risk of accident. The sounds used in this study does not exceed in any case the level emitted by the diesel car and therefore does not increase the noise pollution in urban environments.

Warning sounds with better detectability (stim1, stim6 and stim8) present a similar pattern in their spectral composition. All of them include clearly marked tonal components on frequencies close to 300, 500 and 900 Hz. The results show no relationship between the peak level emitted by the vehicle and his detectability.

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5C.5 References

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