ON THE USE OF SOUND METRICS TO EVALUATE NOISE FROM EVs AND HEVs - A LITERATURE REVIEW

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ABSTRACT

This paper presents a literature review performed within the scope of COST action TU1105, focused on the metrics to evaluate sound generated by EVs and HEVs, either in the driver point of view or in the pedestrian point of view. The topic is addressed, having as a reference the metrics used to assess noise from vehicles powered in a more traditional manner. One of the differences between these vehicles and IC ones is related to the lack of sound signature in low speeds (bellow approximately 50 km/h), therefore warning sound systems are being developed, and will be here discussed.

RESUMEN

Esta comunicación presenta una revisión de la literatura en el ámbito de la acción COST TU1105. El trabajo se centra en las métricas para la evaluación de sonidos generados por los vehículos eléctricos y vehículos híbridos, tanto desde el punto de vista del conductor como de los peatones. El problema es abordado tomando como referencia los indicadores empleados en la evaluación del ruido en vehículos de tracción tradicional. Una de las diferencias de mayor peso entre vehículos eléctricos y de combustión se encuentra en la ausencia de firma acústica a bajas velocidades. Esta circunstancia hace necesaria la incorporación de sonidos de advertencia, siendo uno de los temas tratados en el presente documento.

INTRODUCTION

The socio-economic quest towards developing vehicles with lower CO2 emission is a global goal of the EU and a crucial ingredient for the competitiveness of the whole European transportation industry. It has been motivating an increased focus on alternative powering systems such as the electric and hybrid ones. To be competitive, however, such vehicles must have an acceptable Noise, Vibration and Harshness (NVH) behaviour, not only inside the vehicle, but also outside. One of the main differences between them and IC vehicles is that they provide little or no noise at certain manoeuvres, which may pose major concerns regarding safety of weaker road users such as two-wheelers and pedestrians.

In the last decades, most of the NVH design and problem-solving knowledge gathered has been concentrated on internal combustion vehicles. The new generation of hybrid and electric vehicles poses however different challenges and so novel analysis techniques have to be developed. In addition the limited knowledge on electric and hybrid vehicles is scattered all over Europe. Having in mind this concerns, the European Cooperation in Science and Technology (COST) has hosted action TU 1105 "NVH analysis techniques for design and optimization of hybrid and electric vehicles" with the aim of engaging NVH experts from vehicle industry and renowned research groups in the accumulation, development, dissemination and implementation of such novel techniques.

The present work is framed within the above mentioned COST action, and its main goal is to perform a literature review related to the sound metrics to evaluate sound generated by EVs and HEVs, while displaying also results provided by previous research. Moreover, due to the existing problematic regarding the absence of noise in electric and hybrid vehicles at certain manoeuvres, strategies for warning sounds will be discussed. It is important to mention that the information gathered here was obtained from a literature review using the following sources: collaborative research projects such as Compett or eVADER; Regulations and Technical documentations provided by different organizations (United Nations Quiet Road Transport Vehicle (QRTV) working group, the National Highway Traffic Safety Administration (NHTSA) in the United States or the recent European Parliament draft legislation);papers available, mainly published in conferences but also in international referee journals; classical books on NVH of vehicles.

SOURCES OF NOISE

The vehicle noise can be produced by several sources. Each of them can be related to a specific part of the vehicle and some will be present depending on the propulsion method used. These sources may be more or less important whether the receiver is placed inside or outside the vehicle.

Engine and powertrain: plays an important role or interior noise of vehicles. Generated by the reciprocating and rotational masses such as pistons, connecting rods and shafts. Other sources of vibration come from gearbox, electric generators, valves, belts, chains and tailpipes.

PWM Process: the electric motor is typically a permanent-magnet synchronous motor. The battery DC voltage converts to a magnitude and frequency controlled AC voltage by pulse-width modulation (PWM). The PWM process is dependent on a switching frequency typically located between 5 and 20 kHz. This switching frequency is one of the main contributors to audible noise together with the magnetic noise from the electric powertrain.

Suspension: positioned between the road-tire interaction and the vehicle body. Its vibration transmission must be taking into account since it may act as a filter or amplifier for the vibrations coming from the wheels.

Tires: have a dual role in road-noise, generation and transmission. Tires are responsible for the transmission of the forces between the road and the wheels. The air cavity inside the tire and its acoustic modes must be taken into account as these resonances increase the transmission of forces. The tire/road noise is often compared with the propulsion noise and it becomes more important as speed increases.

Aerodynamic Sources: there are different aerodynamic source in a vehicle. We can distinguish between global flow (low-frequency range), local flow (mid to high frequency range) and turbulence and boundary layer noise (broadband noise).

Other sources: noise can be generated too by means of brakes or electrical and mechanical accessories.

SOUND METRICS IN THE EVALUATION OF NOISE

Evaluation from the Driver Point of View

A standard procedure, known as Sound Quality Process, developed by Ford [2], is one of the classical methods to investigate sound quality in IC vehicles. This method consists of four parts: recording sound samples with binaural measurement system, objective analysis, subjective evaluation of the sound and correlation between objective and subjective evaluations.

The recording process is the most critical step to determine the sound quality. There are several advantages, usually pointed out, in listening to sound recordings instead of to the original sound. It allows each listener to hear exactly the same sound, compare different models by playing the recorded sounds after one-another, determining small differences between sounds, ensure equal test conditions for all members of the jury or eliminate brand and model biased. However, it also has some disadvantages: subjects have no visual clues and vibration inputs are neglected.

Normally, sounds are recorded by means of two condenser microphones in the ears of a binaural head. The use of binaural signals provides a more realistic listening experience if sound is presented via headphones.

The objective analysis of the sound recorded is traditionally performed by measuring metrics such as loudness, sharpness, tonality or fluctuation strength. Methods like Fourier analysis, spectrum vs time analysis, n-th octave analysis, order tracking, metric calculations, filtering or statistical functions are also used to analyse sound quality. These methods are aimed to eliminate the subjectivity in sound quality evaluation process.

Loudness	Subjective impression of the intensity and magnitude of sound. Perceptual measure of the effect of the energy content of a sound on the ear.
Sharpness	Average pitch of a sound. It can be calculated from the curve representing the loudness of a sound in its spectral domain.
Roughness	Created by relatively quick changes produced by modulation frequencies in the region of 25 to 300 Hz.
Fluctuation Strength	Quantifies subjective perception of lower (up to 20 Hz) amplitude modulation of a sound.
Tonality	Presence of dominant tones in sound. Determined by examining the critical band spectrum for impulses and peaks.
Articulation Index	Measure indicating the signal to noise ratio in conversation frequency spectrum (0.5 – 4 kHz) inside a vehicle.
Noise Level	ISO 5128:1980 specifies the conditions for a reproducible and comparable data of noise level.

Other metrics used to describe the perception of tone components are "tonalness", "tone-to-noise ratio" (TNR) and "prominence ratio" (PR). These have been used by the automotive sector particularly to evaluate noise provided by electrical vehicles.

Subjective analysis is a process which gives the human perception of a particular sound. A jury, mostly non-professionals, is gathered, and a number of sounds are presented. The jurors have to rate and compare these sounds, so that the engineer can determine how different attributes of a sound are subjectively perceived.

These tests should be carefully planned. The listening environment plays an important role, should be comfortable and ambient noise levels should conform to NCB 20 criteria.

Jurors should be representative for the test. Vehicle manufacturers establish the use of 25 to 30 subjects for a representative results in automotive sound quality testing.

There are two ways to set up the time that a jury has for evaluation. During the first method, known as *Selfpaced*, the user has control of the test and can play the sounds as many times as deemed necessary. In the second one, call *Paced jury test*, one set of stimuli is presented to several jurors at once. In this case, the operator has control of the durations of the test.

Similarly, several jury evaluation methods exist:

Detection Tasks	Ask a subject to choose which of two sound samples contains a given signal
Evaluations Tasks	Ask a subject to make a judgment of preference between two sound samples
Similarity Tasks	Ask a subject to rate two sounds sample's similarity

Correlation corresponds to the final step into the SQ procedure. It may be performed by different methods: graphical analysis, linear regression or distribution analysis, among others.

Evaluation from the Pedestrian Point of View

In the pedestrian point of view, the acoustic metric commonly used to evaluate noise from a vehicle is the sound pressure level in dB(A). The ISO 362 (part 1, 2 and 3) provides the standards to measure the sound level emitted by vehicles under typical urban traffic environments.

The European Commission has published in the Journal of the European Union (21th of March, 2014) the recently approved legislation on the sound level of motor vehicles [3] which is proposing to reduce the noise produced by passenger cars, light commercial vehicles, buses, light trucks, coaches and trucks. One of the expected revisions of this standard is the introduction of a new technical information to clarify testing of vehicles with multiple propulsion sources, such as Hybrid vehicles.

COMPARISON BETWEEN EVs/HEVs AND ICV NOISE GENERATION

The number of electric and hybrid cars in cities has considerably increased. These vehicles can help to reduce noise pollution, since in general they are assumed to be quieter than internal combustion vehicles.

From the driver point of view

The noise signature from an electric traction motor is characterized by speed-dependent high frequency tonal components from the dominating electromagnetic harmonics, covering a wide rpm-range. With relatively low levels of masking noise from tires and wind, the tonal components can be accented in a large frequency range and contribute to perceived annoyance for the occupants inside the car.

From the pedestrian point of view

From the pedestrian point of view, there are two main sources of noise in vehicles: the propulsion and the contact between tires and road. With the increasing speed, the tire/road noise increases more than the propulsion one, becoming even higher at high speeds. Therefore, if the tires used on electric vehicles are the same as on ICE vehicles, it is expected, at low speeds, that electric vehicles emit lower noise level that the ICE vehicles.

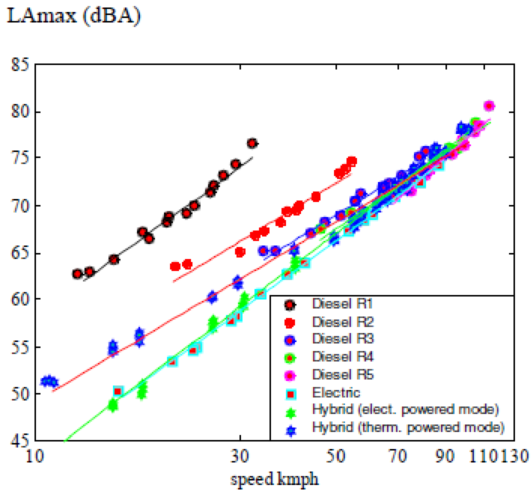
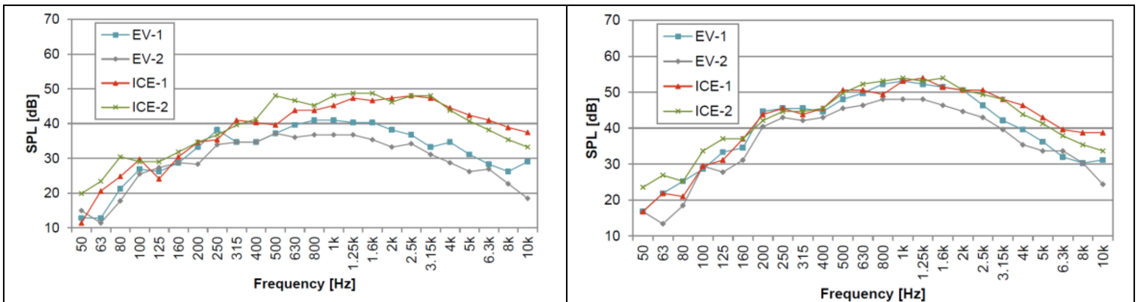


Figure 1: The maximum noise level from different types of cars measured with pass-by measurements. From a French study by Joël Lelong and Roger Michelet, according to [1].

The following figures represent the frequency domain spectrums of noise measured from different ICE and EV models.



a. Vehicles without artificial sound added

b. Vehicles with artificial sound added

Figure 2: The A-weighted frequency spectrums for ICE and EV vehicles driven at a constant speed of: a) 10km/h; b) 20 km/h, according to [1].

The traffic around the cities is characterized by a great number of accelerations, decelerations and braking. Accordingly, in this manoeuvres the electric vehicle display advantages in noise reduction as they are quieter.

Research	Max. Reduction	Speed of NO Reduction	Distance to microphone
1	15 dB at 10 km/h	50 km/h	7.5 m from centre, 1.2 m from ground
2	20 dB at idle	30 km/h	2 m from centre
3	7 dB at 10 km/h	No information	2 m from centre, 1.2 m from ground
4	12 dB at 8 km/h	24 km/h	No information
5	1 dB at 9.7 km/h	32 km/h	3.7 m from centre, 1.5 m from ground
6	9 dB at 9.7 km/h	32 km/h	3.7 m from centre, 1.5 m from ground
7	4 dB at 40 km/h	2 dB at 80 km/h	7.5 from centre, 1.2 from ground
8	4 dB at 30 km/h	No information	No information
9	7 dB at 10 km/h	40 km/h	7.5 from centre
10	10.5 at 10 km/h	No information	3 m from centre, 1.5 m from ground

Figure 3: Table extracted from reference [1] which sums up the maximum reduction level attained with an electrical vehicle and corresponding speed; speed where no difference was found, measurement conditions

Some studies demonstrate the influence of the velocity in the noise generated by electric vehicles as shown in the following table:

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

Table 1: Table extracted from reference [1] which sums up difference in noise between electric passenger cars and ICE passenger cars for different speeds

Some references [4] indicate that noise generated during the acceleration at low velocity is lower for electric vehicles than for combustion ones. However at 40 km/h there is no longer a difference between both.

Regarding the frequency spectrums, several references found that noise from electric vehicles can have more peaks at middle frequencies. However, the noise spectrum from ICE vehicles can also have peaks but these tend to be at lower frequencies. The peaks at middle frequencies for electric vehicles can be a problem as the human ear at these frequencies is much more sensitive and can perceive the sound as annoying.

Although electrical cars may offer advantages in noise reduction, some factors as their frequency content can influence the way the noise is perceived. Some electric motors have single frequency tones, which can be perceived as annoying.

STRATEGIES FOR EXTERIOR WARNINGS

Vehicles operating in all-electric mode produce less noise than traditional combustion engine vehicles and hence can make it more difficult for pedestrians, blind and others to be aware of their presence. A study performed by the National Highway Traffic Safety Administration [5] conclude that HEVs are two times more likely than ICE vehicles to be in a pedestrian crash. The following situations have been highlighted: backing out, slowing/stopping, starting in traffic, entering or leaving a parking space and turning. For these reasons it is necessary the use of warning sounds designed to alert pedestrians of the presence of electric drive vehicles travelling at low speeds.

Warning sounds could be based on recordings of actual ICE vehicles made at various speeds and under various operating conditions. As a second alternative the sound can be generated by a digital signal processor chip programmed to emulate the sound of an ICE, at least in the range of 300 to 5000 Hz.

Regarding the safety, the essential characteristics of the warning sounds are related to its audibility, locatability and directivity. From the environmental point of view, the most important features are its directivity, the attenuation and the acceptability.

Audibility: the audibility is a function of its loudness. The warning devices should have a sound pressure level (SPL) equal to that of a typical ICE vehicle at the same distance. For optimal audibility a frequency band from 0.5 kHz to 3.5 kHz is recommended.

Locatability: optimal for a frequency band from 0.5 kHz to 4 kHz. Range of 0.5 to 1.5 kHz provides information about the angle from centre line. Frequencies up to 3 kHz indicates left or right centre line. 3 kHz and above indicates information about front or rear.

Directivity: the spatial characteristics of acoustic radiators is defined in terms of its directivity which defines the relative level of the sound pressure around the source at any given frequency. Uniform radiation all around the vehicle is undesirable, for safety and environmental reasons. An SPL guideline reduction of 3 dB(A) at ± 45º and up to 10 dB(A) at ± 90º is suggested to provide audibility at a safe distance outside the edges of the vehicle's wheel print.

Attenuation: the wider de frequency band, the greater the attenuation with distance. For optimal attenuation, a frequency band from below 1 kHz to above 5 kHz is recommended.

Acceptability: implies a sound which presents its warning characteristics in an inoffensive manner.

Countries such as Japan and U.S. approved legislation related to EV warning sounds in 2010. The European Parliament approved in April 2014, a legislation [3] that requires Acoustic Vehicle Alerting System (AVAS) for all new electric and hybrid vehicles, with a transitional period of 5 years to comply with the regulation. This document sets out a set of measures concerning these systems, among which the followings were selected, within the aim of the present work: the AVAS shall automatically generate a sound in the minimum range of vehicle speed from start up to approximately 20 km/h and during reversing; the sound to be generated by the AVAS shall be a continuous sound that provides information to the pedestrians and other road users of a vehicle in operation; the sound should be easily indicative of vehicle behavior and should sound similar to the sound of a vehicle of the same category equipped with an internal combustion engine; the sound to be generated by the AVAS shall be easily indicative of vehicle behaviour, for example, through the automatic variation of sound level or characteristics in synchronization with vehicle speed; the sound level generated by the AVAS shall not exceed the approximate sound level of a vehicle of the M 1 category equipped with an internal combustion engine and operating under the same conditions.

Metrics to Evaluate Warning Sound Systems

One parameter to evaluate a warning sound system is the maximum sound level it provides, which may be measured using the new test method defined in the recently approved European Union legislation [3].

Another parameter to evaluate a warning sound system is the minimum sound pressure level. Within the European Union, the ISO committee has been working on a draft document to evaluate this metric, which is under discussion process. The ISO/CD 16254:2012 "Measurement of minimum noise emitted by road vehicles" defines the procedure to quantify the characteristics of any external sound generation system installed, with the purpose of conveying acoustic information about the approaches, presence or departure of the vehicle to nearby pedestrians. One of the issues regarding this document is that it proposes a distance for measuring the noise of 2 m.

In the United States, NHTSA has been performing research on the use of other parameters. In the report [6] are proposed, besides the minimum sound level, a set of parameters and also minimum requirements that EVs and HEVs shall meet in order to pedestrians detect vehicle presence, direction, location and operation. The performance requirements shall allow a pedestrian to reasonably detect a nearby EV or HV driving at constant speed, accelerating, decelerating and operating in any other scenarios that NHTSA defined as appropriate.

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, 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)

CONCLUSIONS

From the analysis carried out, the authors verified that recent research on the sound metrics related with EVs and HEVs has been addressing mostly the issue of sound parameters used to evaluate sound in the pedestrian point of view. This focus is mostly motivated by the goal of countries in decreasing sound pollution while providing pedestrian safety. Considerable research has also been performed on warning sounds. Warning sounds systems resembling the noise generated by IC vehicles are preferred. Some of the results from research are being used in the form of recent regulations, such as in the European Union, United States and Japan. As for the parameters related with interior noise evaluation, less studies were found in the sources used to perform the literature review and it was not clear how the classical psychoacoustic parameters correlate with subjective perception. Other parameters more common in the evaluation of Information Technology equipment or telecommunication may also be suitable for interior noise evaluation.

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