The sound of silence of electric vehicles – Issues and answers

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ABSTRACT

Electric or hybrid vehicles represent moving silent objects in potentially complex environments. As such, they definitely can be considered either as a blessing, with regards to noise pollution, or a curse, with regards to user-experience. In an ecological analogy – and all things considered –, the advent of this new type of mobility artefacts can be compared to the introduction of a new species in a given ecosystem that should find its right place by means of external signs embodying its reality with regards to others. On the basis of this approach, and because these quiet vehicles (electric, hybrid or even recent quiet internal combustion engine cars) mostly tend to exist in noisy and heterogeneous urban environments, it seems inevitable to tackle issues related to their silence. This leading property (quietness) should be studied, designed and formalized in order to provide relevant and efficient answers to the main problems they address, at least, for the next few decades (before the other noisier species finally disappear …). Within this scope, the paper will present a synthesis of the topic: firstly, by setting out the context of use (silent vehicles and accidentologic situations); secondly, by inventorying several proposed solutions (driver or pedestrian -centred); thirdly, by argumenting the sound design approach and presenting some prototyped or industrialized solutions; and fourthly, by giving the basis and the recent developments on normative works that are undertaken at national or international levels.

Keywords: Quiet vehicles, Sonification, Standards / I-INCE Classification of Subjects Nb.: 13, 68, 81

1. INTRODUCTION

Even today, the silence of electric vehicles remains an open question from a scientific, environmental and societal point of view. It has progressively moved into the political arena owing to the different legislation brought in – or under consideration – in several parts of the world (United States, Europe and Asia in particular). On the broader front, this question also embodies in its own way one of the key ideas which R.M. Schafer puts forward in his seminal work entitled "The Tuning of the World" (1) in which he predicts a "synthetic soundscape in which natural sounds are increasingly replaced by artificial ones" (2).

At this stage, the issue is therefore as follows: why give sound to a silent object and risk increasing the background noise in our already overpopulated towns saturated with all kinds of noise, mostly unwanted (by the listeners) and uncontrolled (by the stakeholders)? Why not make the most of a silent innovation (at last!) to move towards reducing the sound levels and road traffic noise to which millions of people are exposed on a daily basis. Conversely, how can this new type of silent vehicle be integrated into our sound ecosystems efficiently and discernibly (noticeably) whilst remaining highly ecological?

We support the theory that the answer to these not at all trivial questions lies in a controlled but nevertheless creative approach to the problem in the context of an intelligent, responsible design process. By incorporating the basic regulatory specifications, this process would reflect more broadly on the composition of the soundscapes of tomorrow in keeping with some of Schafer's precepts such as: "To understand what I mean by sound design, let us consider the world as a huge musical composition constantly playing out before us" or "[…] the soundscape is not an accidental

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by-product of society but rather, a deliberate creation, a creation which is remarkable as much by its beauty as by its ugliness." (2). Controlled, this sound design could also be a solution to fears developed in some studies - and to some extent justified - predicting that the combination of several continuous noises (linked to several electric vehicles) could result in an unbearable din (3).

To support this theory, the paper first of all aims to review the specific context in which electric vehicles are used, identifying in particular the potential risk of accident they incur. It will then seek to formalise the different concepts offered as solutions and present a comparison of industrial or prototype projects already implemented. Finally it will take stock of the normalisation work ongoing in this field.

2. CONTEXT OF USE

The apparent "silence" which constitutes one of the attractions of electric vehicles in turn leads to fears for pedestrians' safety. Removing the noise of the combustion engine running at low speed could be the cause of increased dangerousness of these silent vehicles and be the source of hitherto unknown accident situations.

2.1 What is a silent vehicle?

Electric and hybrid vehicles can be very quiet at low speed, making them difficult for pedestrians to detect. The sound level of a vehicle and the resulting perception of it depend on its speed and the distribution between the noise made by the means of propulsion, contact between the tyres and the road surface and at higher speeds, aerodynamic-type noises. For an internal combustion vehicle, the engine contributes significantly to the overall noise made by the vehicle, especially at low speeds. Figure 1 shows the noise level generated when three vehicles go by, according to their speed. At low speed, the difference between a vehicle with an engine and an electric vehicle can be significant (over 10 dB(A)). Above 20 to 30 km/h, the noise made by the tyres on the road surface becomes dominant and the differences become less pronounced. This difference at low speed is due to the low sound emission of the electric motor as compared to the internal combustion engine.

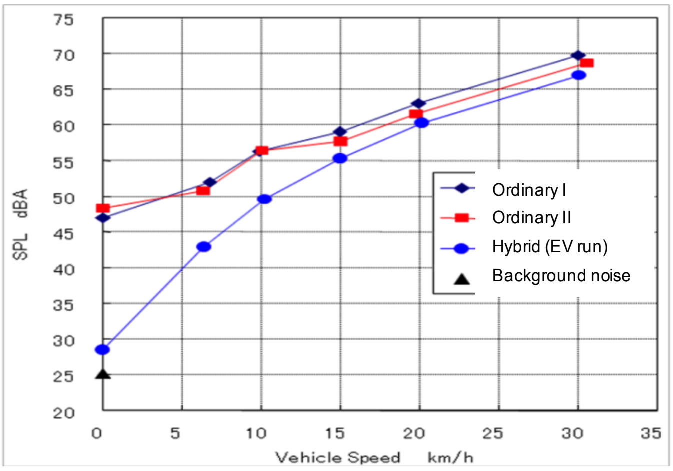

Figure 1 - Sound emissions from combustion engine vehicles (Ordinary I and II) and hybrid vehicles in electric mode (21).

On this basis, one of the questions addressed in this article - and more widely in the work conducted on the subject - can be summarised as follows: how can a silent vehicle be made audible?

2.2 The dangerousness of silent vehicles

The dangerousness of silent vehicles can be established based on accident studies or studies comparing the distances at which they can be heard. Under certain conditions and at low speed (10 km/h), an electric vehicle may not be detected until it is less than 5 metres away, whereas under the same conditions, a vehicle with an engine can be heard up to 50 metres away (4). Taking into consideration all the data collected, the target zones identified are those where vehicles are at a standstill or moving at slow speed (< 20-30 km/h). In these configurations, masking by background noise is a key factor. Background noise levels linked to these zones are deemed to be less than 55 dB

(Lden). Taking the example in Figure 2, a vehicle with an engine is clearly audible above background noise of 55 dB(A) whereas an electric vehicle is not.

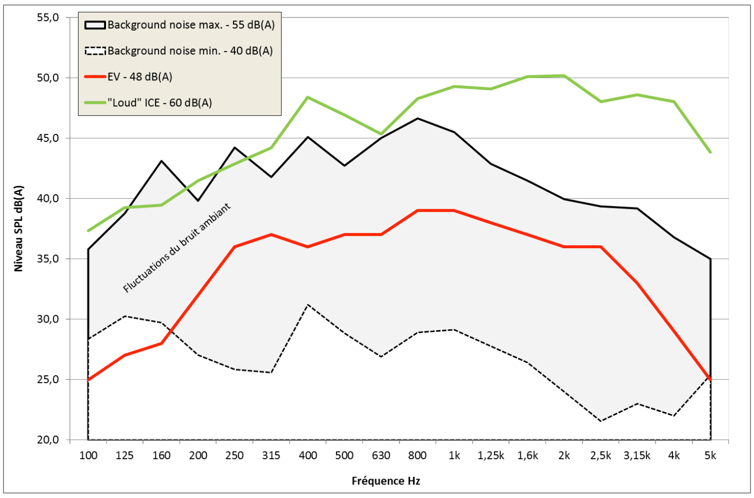

Figure 2 – Variation in the emission spectrum: background noise, internal combustion vehicle (green) and electric vehicle (red)

Associations for the blind and visually-impaired, naturally among those most affected, have had no difficulty convincing the authorities of various countries to take their concerns into account and legislate on the subject (5). On the other hand, alternative opinions also provide strong arguments against the sonification of vehicles and call for solutions deemed to be less “harmful” for the environment (6).

2.3 Accident data and situations

Taking acoustic and visual considerations as a starting point - and not only targeting electric and hybrid vehicles but all collisions between pedestrians and vehicles - it is possible to infer the critical aspect of certain situations more accurately in terms of detectability. Recent perceptual studies use a type of vehicle path or behaviour which is relevant from the point of view of pedestrians, particularly the visually-impaired. For example, in their experimental protocols, Ashmead et al. (7) consider the vehicle passing in front of the pedestrian (right-left), passing alongside (left) and also passing alongside (left) + turning right, thus simulating a pedestrian at a T-junction who has to decide whether or not to cross based on detection of the traffic flow to their left and the potential presence of vehicles turning right (Figure 3).

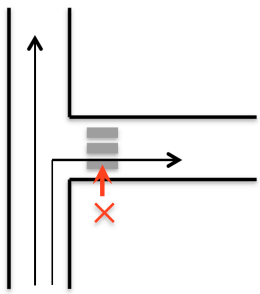

Figure 3 - Illustration of lateral and lateral right-turn trajectories according to Ashmead et al. (7)

This being said, very little objective data analyses and quantifies these risk situations. One of the references on this matter is a study by the NHTSA (8) which shows that in the United States, the rate of collision between electric or hybrid vehicles and pedestrians is 0.9% where as it is only 0.6% for internal combustion vehicles. This difference is globally significant according to the study, and all the more so if we consider low-speed operations (slow forward movement, reversing or leaving a car park) - although the authors recommend a degree of caution when interpreting these results due to the small size of the sample analysed.

However, another study conducted by the TRL (9) gives slightly contradictory results. It shows that the proportion of accidents involving electric or hybrid vehicles is lower than for internal combustion vehicles, whether considered in total or with pedestrians in particular. Nevertheless, the study reveals that these vehicles are also used differently, in particular limited to urban usage, which may reduce the total proportion of accidents involving them. It also indicates that the data is too limited to allow a proper interpretation with regard to the location or manoeuvres linked to accidents involving pedestrians and the risk to the blind.

Moreover, other institutes such as the JASIC in Japan or the SWOV in the Netherlands have carried out their own accident analyses and also reach the following conclusion: although there is an upward trend in accidents between pedestrians and electric vehicles, it is nevertheless difficult to clearly show this, given the low percentage of this new type of vehicle in the overall fleet (10) and also due to the fact that most accidents happen at low speed, only causing minor damage and are therefore difficult to count (no accident report or police report) (11).

3. CONCEPT OF SOLUTIONS

Solutions studied in recent years to address the problem of the dangerousness of electric vehicles reveal two conceptually different approaches. The first "driver-centred" approach delegates risk management to the person in charge of the vehicle and gives them the ability to indicate their presence in their environment, particularly through their attention and vigilance, aided where necessary by driver assistance systems. The second "pedestrian-centred" approach considers that the pedestrian - or more generally the person moving in the vicinity of the vehicle - must be able to grasp and analyse their surroundings at all times to enable them to make the right decisions (e.g. orientation or navigation). This approach therefore requires that all elements in the environment should be naturally perceptible and in particular, audible.

According to another point of view, the same problem can be analysed based on the terminology of Sandberg, i.e. in "acoustic / non-acoustic" terms (12). This categorisation remains relatively orthogonal to the previous concepts and allows the problem to be considered in a two-dimensional space. A possible solution would be a driver-centred non-acoustic measure (e.g. driver training) or an acoustic measure (an intermittent warning signal such as a bell). A pedestrian-centred non-acoustic device (such as a tactile information system relayed by smartphone type mobile terminals) or acoustic system (a deliberate sound signature which adapts to the exterior environmental conditions if necessary - background noise, day/night, weather, etc.) could also be possible.

3.1 Driver-centred approach

3.1.1 Driver training

The awareness of drivers of electric vehicles can be raised before they get into their car through different kinds of information:

- how unobtrusive and difficult to detect their vehicle is for pedestrians,
- the danger this type of vehicle represents for the blind and visually-impaired,
- the driver's responsibility in preventing risk situations.

This is a type of behavioural solution recommended by Sandberg in particular (12) and documented by Cocron et al. (13) and Hoogeveen (14) during their large-scale experiments.

The experiment conducted by Cocron et al. (13) involved a fleet of 40 electric vehicles (without added sound) and their users over a period of 6 months. It looked into the role of silent vehicles in the driver's user experience and the relationship between vehicles and pedestrians. It was conducted by means of a questionnaire filled in by each driver at the start, halfway through and at the end of the test. Only a few minor incidents were identified during the experiment. One of the main outcomes lies in the fact that most of the drivers declared that they had learnt to drive this type of vehicle, in particular quickly learning to recognise potentially dangerous situations. They were particularly vigilant when parking or moving at slow speeds and systematically adopted a driving approach based on anticipation. This could argue in favour of a specific driving license for silent vehicles.

Hoogeveen (14) took a similar approach to investigate the problem. A questionnaire dedicated to EV users was posted online in order to explore general questions as: "Which kind of sound a quiet vehicle should be produced?", "Are there potential dangerous traffic situations with quiet vehicles?", "What are your behavioural changes while driving an electric vehicle?", "Do you have possible suggestions for safety improvements?". Main outcomes are that 1/3 of participants (36%) estimates that electric vehicles are safe but 2/3 of participants (69%) "changed their driving behaviour when driving an electric vehicle instead of an internal combustion engine vehicle". Moreover, the results also claim for a change of behaviour of "other road users", and especially pedestrians that should "look instead of listen" when crossing streets. Finally, if an added sound is to be implemented, a large number of persons would prefer a "warning sound" than a "driving sound"; the former being judged sufficient and less environmentally intrusive with regards to overall noise annoyance.

3.1.2 Urban warning devices

Road vehicles are equipped with regulatory warning devices, commonly known as "horns" and defined in UN ECE28 [UNECE Audible warning devices and of motor vehicles with regards to their audible signals]. They are used in situations of immediate danger and therefore cannot be employed simply as devices to alert pedestrians as they are too loud. Their direct effect would be to increase the level of background noise and the discomfort this causes, and would not bring out the right reaction in pedestrians.

Having said that, some vehicles, particularly public transport vehicles (buses, tramways) are fitted with a second type of urban warning device. These "gentle warning devices" - as described and recommended by Sandberg et al. (6) - emit quieter noises, generally based on bell sounds, allowing drivers to warn pedestrians of the presence of their vehicles without surprising them or being aggressive.

Thus, being mounted on a silent vehicle and operated when necessary by the driver, this device can replace the regulatory warning device in many situations which do not represent an immediate danger and reduce noise nuisance in towns whilst allowing the electric vehicle and its driver to signal their presence.

3.1.3 Driver assistance

A growing number of vehicles are currently equipped with ADAS [Advanced Driver-Assistance Systems]. Among these, braking assistance systems (ABS, AEB) combined with pedestrian detection constitute operational solutions allowing the accident risk of electric vehicles to be reduced. These devices can warn the driver when an obstacle is in or close to the vehicle's trajectory and provide a secondary safety mechanism by managing braking. They are now included in EuroNCAP assessments and are also developed with the aim of producing autonomous vehicles, an emerging theme in the field of new mobility.

Combined with increased driver attention and manual warning systems (see sect. 3.1.2), driver assistance devices provide an additional solution. This is notably what Sandberg recommends (12), arguing that there are many non-acoustic solutions to resolve the problem posed by the unobtrusive nature of silent vehicles and that it would be more beneficial to contribute to the reduction of the noise produced by vehicles rather than adding additional noise which would in the long term increase the background noise in towns. This type of device, in particular pedestrian detection, is also used in pedestrian-centred solutions to better address the sound signature emitted by electric vehicles (see the eVADER project - sect. 4.1).

3.2 Pedestrian-centred approach

3.2.1 Distributed cooperative solutions

Solutions based on Information and Communication Technologies (ICT) tend to make silent vehicles "smart" and therefore able to dialogue with mobile communication units, which almost everyone has nowadays (*smartphones*). The expected generalisation of possibilities for communication between vehicles and road and infrastructure users will thus allow the vehicle to better understand its environment via preventive means adjusted to each situation. In the medium term, it is technologically perfectly possible for the vehicle to provide a pedestrian in its vicinity with information concerning its presence or behaviour on their mobile phone. However, this technology still needs more development both with regard to functionality and communication. It is therefore not possible to consider its use at present.

Looking to the future, this is the solution designed by Owen (15) offering a paradigm for encoding traffic data as vibratory information. The application is developed on mobile phones and uses wireless communication protocols to receive information from vehicles. The encoding principle is based on pulse amplitude modulation according to the presence and speed of a vehicle, each vehicle having its own vibratory signature. When tested experimentally, the principle proves to be more appropriate to informing of the presence of the vehicle rather than its speed. However, this approach needs to be improved and possibly supplemented by an audible - not just haptic - system to transmit information.

3.2.2 **Adding sound to vehicles and sound design**

In view of the reduction in noise due to the electric motor, the most logical solution may be to maintain noise artificially, allowing the vehicle to exist in the soundscape and enabling the pedestrian to benefit from useful information for navigation again. This configuration recreating a similar sound emission situation to that of the internal combustion engine but this time with a sound which has been designed, and therefore controlled, and possibly innovative - therefore not necessarily based on the sound of a traditional engine -, may satisfy all the environmental requirements linked to this new context.

Adding sound to the electric vehicle is a case-study which is both conceptual and practical. It is emblematic for sound design, the aim here being to replace silence by sound on the basis of functional specifications and aesthetic concerns which are potentially important in terms of brand image and sound identity. This approach addresses key issues such as safety, ergonomics, the sound environment and ecology, whilst remaining fundamentally attached to the idea that sound design is in no way synonymous with escalating noise and sound pollution.

This last point is worth remembering insofar as it is often used by opponents to acoustic solutions for silent vehicles (see section 3.1) and sheds light on the real added value of a sound design approach to the issue. In fact, in no way does this involve "simply" adding sound in relation to the background noise in which the vehicle operates. It really does mean analysing the environment to find solutions which are acoustic (e.g. the use of specific frequencies), perceptive or cognitive (e.g. use of masking phenomena or learning mechanisms) or technical (e.g. use of adaptive processes) to achieve a solution that is compatible with the concept of sound ecology yet at the same time meets basic warning requirements. It also involves reaffirming that the aim of sound design is to generate sound comfort rather than nuisance.

4. EXAMPLE OF REALIZATIONS

In terms of tangible realizations, the challenge mainly needs to fulfil two opposite requirements: providing the highest detectability while ensuring the lowest noise impact on the environment. Moreover, from a user-centred and inner-car point of view, it has also to take into account the need to be informative for the driver, and not disturbing for his driving activity. These constraints will ideally lead to the definition of efficient, relevant and acceptable sound signatures for electric vehicles. In the following sub-sections we will briefly present and compare two different methods of conception. The former can be considered as analytic and globally results from an inductive approach: from basic acoustic/perceptual rules, it uses simple signal parameters and leads to analytic sonic solutions. The latter can be considered as synthetic and globally results from an abductive approach (16, 17): from standard but also more unconventional sources of inspirations, it uses complex sonic materials and leads to aynthetic and possibly more innovative sonic solutions.

4.1 Analytical approach

Previous investigations on the quietness of electric vehicles have contributed to understand different signal parameters and their respective influence on the detectability and/or annoyance of acoustic signatures. First of them is the eVADER[3] project which one specific task was to propose the design of experimental stimuli built upon acoustic parameters and rules selected on the basis of relevant perceptual or cognitive principles. The parametric design of these warning sounds was done from a consistent literature review collecting general knowledge about – amongst others – physiological mechanisms (sensitivity, masking), auditory scene analysis principles (segregation, grouping), cognitive notion of salience or, more generally, acoustic warning strategies (18). These theoretical inputs lead to take into account three basic parameters: harmonic complexity, frequency and amplitude modulation (19).

A second related work has been conducted in the MetaSon[4] project that aimed at defining the semiotical content of the sounds as well as the acoustical variables relevant for a perceptual and interactive control of these sounds by the use of synthesis. Should we simply inform the pedestrian that a vehicle is arriving or should that sound specify to the pedestrian that this vehicle is accelerating or slowing down? The studies conducted in MetaSon demonstrated the relevance of parameters such as pitch and level (20).

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[3] http://evader-project.eu

[4] http://www.agence-nationale-recherche.fr/?Project=ANR-10-CORD-0003

Other studies considered parameters such as position of spectral peaks, frequency modulation and pitch (21) or decomposed the proeminent acoustic features for detectability in a 3-state spectro-temporal space: continuous / modulated / impulsive temporal morphologies on the one hand, and harmonic / inharmonic / noisy spectral contents, on the other hand (22).

4.2 Synthetic approach

Some years ago (2009-2012), this same topic was implemented in an industrial collaboration between a car-manufacturer (Renault) and a research team (Ircam – SPD team) associated with a composer / sound designer (Andrea Cera). The scientific and creative procedures underlying this work specially highlighted the question of inspiration. Actually, due to a kind of "blank page" configuration at the beginning of the project (few works done on that topic before), the traditional scientific state-of-the-art was completed with unconventional inspirational starting ground such as study of the cinema's sonic imagery or expectations about how electric cars should sound.

Despite a relative low volume of research on the topic – at the time of the project –, a standard bibliographic review was achieved anyway. Among the works, two linked studies were especially taken into account. The former produced verbal description of typical sounds to be ideally implemented on electric vehicle: music, whistle, beeps, horn, clicking, exhaust pipe, engine (23). The latter started from these categories and conducted an acceptability experiment based on an audio-visual paradigm and an evaluation scale where engine sounds (grouped together with hum and white noise) were rated as the most acceptable and preferred whereas horn sounds (grouped together with siren and whistle) were rated to be the least ones (24).

In addition, part of the initial inspirations was based on a movie analysis of sequences showing futuristic cars, hypothesizing that public expectations on the nature of EV's sound – and hence its acceptability – could partially be shaped by the sound design work done in these science fiction movies. Then, specific elements were extracted and studied: jet sounds of the Lola T70 in THX 1138 (25), gentle drones of the converted vintage cars in Gattaca (26) or hummings of the next generation vehicles in Back to The Future Part II (27). The main outcomes were that, for these new forms of engine, sound designers tended to shy away from reality, and shift towards drone-like, continuous sounds, with timbral qualities adapted to shape and performance of the car, rather favouring the perception of a continuous layer of sound than the emergence of discrete elements. Nonetheless, examples coming from movies have to be considered with care as their caricatured and ephemeral nature is in great contrast with the more ubiquitous and constant sonic presence of a car sound in everyday life.

4.3 Soundness of sound design

Moreover, an interesting – and independent – a posteriori comparison between these two methods occurred at the end of the eVADER project and showed, to a certain extent, the legitimacy of a controlled sound design approach in such a complex context and framework.

Actually, one experimental task of the eVADER project was to evaluate the parametric process used for the design of the warning sounds (see sect. 4.1). It was conducted by means of in situ listening tests with regards to two main criteria: "detectability" – measured by a response time protocol – and "unpleasantness" – assessed on a semantic scale – (28, 19). The data resulting from these tests allowed to locate in a detectability/unpleasantness perceptual space the basic-rule-based conceived stimuli (Figure 4).

But, in a final round of experiment that occurred at the very end of the project (29) the basic stimuli were mixed with the sound signature that have been specifically designed in the framework of the synthetic method presented in the previous section (4.2) – called "brand sound" in the corresponding Deliverable document (D6.5) and on Figure 4. One of the main output of this ultimate test showed that the brand sound seemed to be better – or at least as well – positioned in the detectability/pleasantness space than most of the initial basic stimuli so that it could almost be included in the "green zone" corresponding to an optimal combination with regards to both detection and agreement (see Figure 4 for depiction).

In a nutshell, this objective result shows that (well-) designed sounds can bear comparison with 'laboratory stimuli' – i.e. sounds designed on the basis of formal rules – and, second, that the sound design process – i.e. the integration of scientific/technical components into more innovative practice – can effectively bring something else in the conception of sound signatures, that is moreover compatible with both information and acceptability needs.

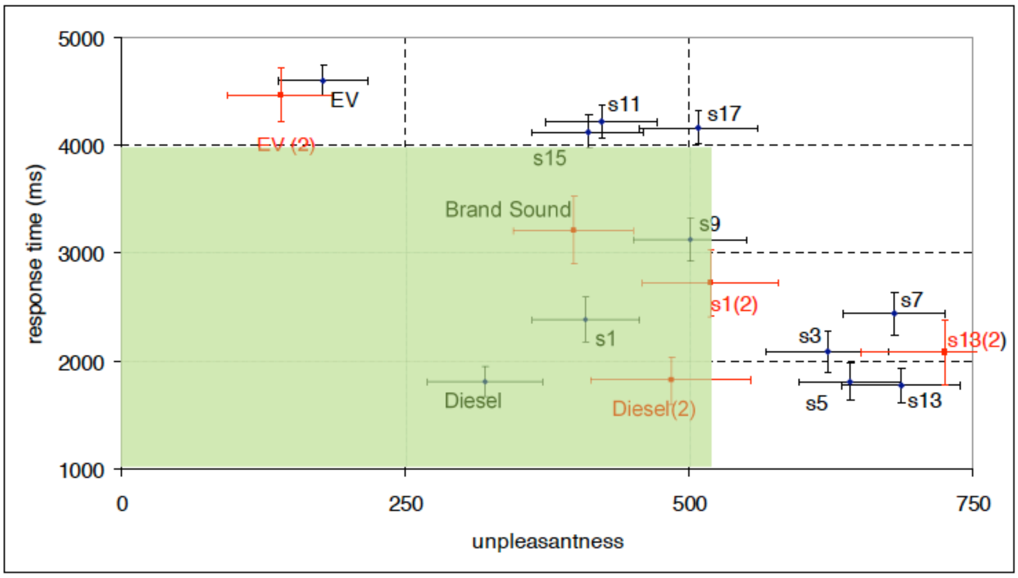

Figure 4 – Detectability vs. Unpleasantness obtained after perceptual experiments. Black points (•} indicate results from a 1st experiment only involving basic stimuli. Red points (•) indicate results from a 2nd experiment including the "brand sound". The green zone represents the "better compromise between detectability and unpleasantness" (taken from (29 – Figure 13), with the agreement of the author)

5. DEVELOPMENT OF THE REGLEMENTATION

Adding sound to an electric vehicle raises many questions insofar as pedestrians and drivers (or passengers) expect it to be silent above all. The sound level both inside and outside the vehicle is therefore an important component to take into consideration for the acceptability of sound signatures and the discomfort they could potentially cause. It is therefore important and necessary to reduce the overall noise level of the vehicle whilst at the same time ensuring sufficient safety for pedestrians.

5.1 Regulations around the world

Japan is no doubt the first country in the world to have considered and addressed how to improve the detectability of silent vehicles. Indeed, it was in this country that devices emitting sometimes very exotic warnings emerged (for example a "beep beep" followed by "*Excuse me. Car is coming!*" or a tune from a cartoon). It is also here that a guide has already been produced and its application recommended for any device mounted on a vehicle.

The United States was also a pioneer in the field, taking the issue to national level with the publication of the Pedestrian Safety Enhancement Act of 2010, for which FMVSS regulation 141 [Minimum Sound Requirements for Hybrid and Electric Vehicles] was published in 2017.

Based on the Japanese guide, the United Nations introduced a similar voluntary guide in 2012, [UNECE Consolidated Resolution on the Construction of Vehicles (R.E.3)], which was then taken up by the European Union in a regulation (540/2014/EC) [Regulation (EU) No.540/2014 of the European Parliament and the Council of 16 April 2014 on the sound level of motor vehicles and of replacement silencing systems]. In 2016, the United Nations published a regulation transcribing these recommendations into specifications requiring the performance of tests for vehicle approval. In 2017, the European Union introduced these same criteria in regulation 540/2014/EC, making it obligatory to fit a sound device on all electric or hybrid vehicles by 2019.

Other countries such as China, Taiwan and Korea are also considering legislation based on the United Nations regulation.

5.2 The voluntary guide

The guide sets out the main guidelines developed for manufactures for the installation of a warning sound system on vehicles:

• the sound must be generated automatically based on the movement of the vehicle until it reaches a speed of at least 20 km/h, and when reversing.

• the sound emitted must be continuous and clearly indicate the conditions under which the vehicle is operating (e.g. automatic variation of the noise level or other characteristics according to the speed of the vehicle). Some sounds are prohibited such as alarm signals (siren, horn, chime, bell and signals used by the emergency services), tunes, noises made by animals, insects or any other sound which could cause confusion in identifying the vehicle or its behaviour (speed, acceleration, etc.).
• vehicles may be fitted with a means of pausing or reducing the sound. In this case, some ergonomic precautions must be taken, e.g. making the function accessible, visual feedback or the reactivation strategy.
• the noise level emitted must not exceed that of an internal combustion vehicle.

5.3 Regulatory requirements

Several criteria are necessary to provide a solution to the problem. To achieve this, the vehicle must be detectable, recognisable and possible to situate whilst at the same time generating low noise nuisance. The main relevant criteria taken into account are the content and frequency level, and the modulation and spectral variation according to speed. These regulatory requirements are broken down into two regulations: UN-ECE R138 and FMVSS 141.

5.3.1 Frequency content and noise level

For UN-ECE R138, detectability is provided by the emergence of:
- at least two 1/3 octave bands between 160 and 5,000 Hz, one of which is at least lower than 1,600 Hz. Minimum levels are required for these two frequency bands and overall levels over the entire spectrum.

For FMVSS 141, detectability is provided by the emergence of:
- either at least four non-adjacent 1/3 octave bands distributed over at least 9 bands between 315 and 5,000 Hz. Minimum levels are required for these 4 frequency bands;
- or at last two 1/3 octave bands, one of which is between 315 and 800 Hz and the other between 1,000 and 3,150 Hz. Minimum levels are required for these 2 frequency bands and the sum of them.

These minimum thresholds are required for forward drive up to 20 km/h for UN-ECE R138 and up to 30 km/h + reverse for FMVSS 141 (Figure 5)

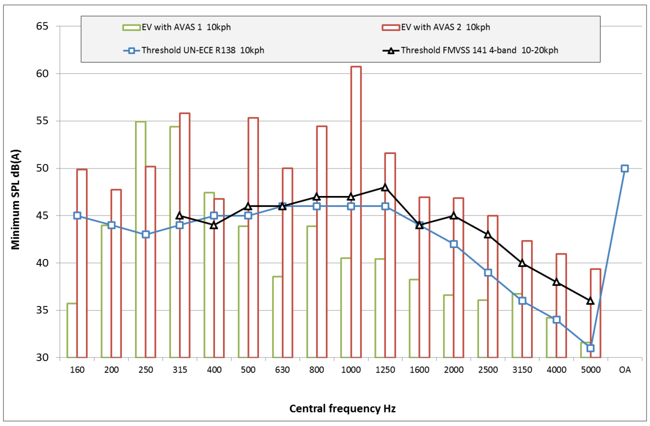

Figure 5 - FMVSS 141 / UN-ECE R138 minimum sound level thresholds and emission spectra for two vehicles with sound at 10 km/h

5.3.2 Noise at a standstill

Some parties deem this to be a fundamental safety element whereas others consider that vehicles at a standstill do not represent a danger, and the noise emitted may even mask the noise of another moving vehicle or one ready to go. This would lead to pointless noise nuisance both for local inhabitants and occupants of the vehicle. This specification is obligatory for regulation FMVSS 141 whereas it is optional for UN-ECE R138.

5.3.3 Frequency variation

Variation in sound according to the frequency is typical of a road vehicle. Moreover it is a possible means to avoid confusion with other types of noise. Furthermore, variation in frequency in line with the speed of the vehicle allows transient phases of vehicle operation (acceleration and deceleration) to be detected. For UN-ECE R138, the level of variation must be greater than or equal to 0.8% per km/h between 5 and 20 km/h.

5.3.4 **Considerations regarding potential noise nuisance**

Finally, a maximum noise level is defined for UN-ECE R138 as there is always a risk of seeing the appearance of vehicles with high noise levels even though there is little likelihood of manufacturers developing solutions with high noise levels which could have a negative impact on the discomfort experienced inside the vehicle.

5.4 Measurement method

Whatever the regulation (UN-ECE R138 or FMVSS 141), the test method is similar and based on standard ISO 16254 [Acoustics – Measurement of minimum noise emitted by road vehicles, 2016]. This standard describes the protocols used to measure the minimum sound level (global and in 1/3 octave bands) and the variation in sound according to frequency.

5.4.1 **Noise level test method**

Tests are conducted on a track, the characteristics of which are described in standard ISO 10844 [Acoustics – Specification of test tracks for measuring noise emitted by road vehicles and their tyres]. Microphones are positioned on line PP' 2 m from line CC' (instead of the usual 7.5 m) and 1.2 m above the ground. The vehicle is driven along line CC' between lines AA' and BB' (Figure 6a). The maximum weighted noise level A is read on each side of the vehicle, either on the track between AA' and PP' or on a test bench for 5 seconds.

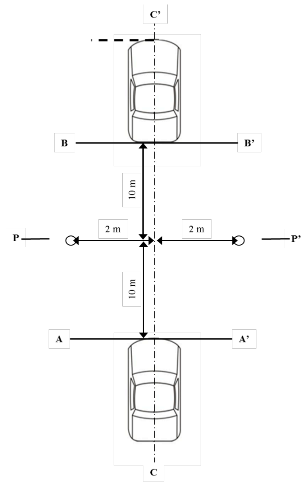

Figure 6a (left) – Test track for noise level measurement (after ISO 10844 norm).

Figure 6b (right) – Measurement in the new indoor installation at UTAC CERAM (Montlhéry, France).

The new UN.R138 regulation published in 2016 is the first regulatory text to have introduced regulatory measurements indoors. On the track, measurement of vehicle noise levels is highly dependent on the background noise. Some vehicles with low noise levels can be difficult to measure. The text therefore provides the possibility to perform the measurement in a semi-anechoic chamber on a roller test bench (Figure 6b).

5.4.2 **Test method for sound variation with speed**

For moving vehicles, several methods are specified to measure the variation in the signal according to speed. The principle consists in identifying one of the frequencies which changes with the speed and then measuring it at different speeds. A variation level in Hz/(km/h) is then calculated. This measurement can be conducted on a track during noise level testing but the spectral processing is not very accurate. Measurements indoors are more suitable to achieve a precise result (Figure 7).

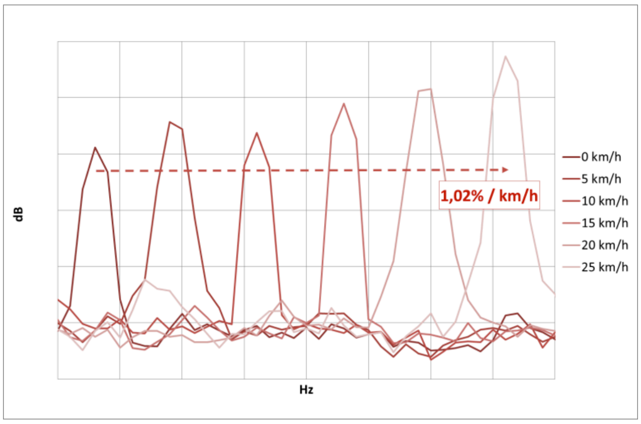

Figure 7 – Evolution of the AVAS spectrum with speed

6. CONCLUSIONS

This article has tried to present the reality and complexity of the problem raised by the quietness of a new generation of electric and hybrid vehicles. These new unobtrusive, mobile objects exist in a noisy heterogeneous environment and must be perceived and understood by their external surroundings either autonomously or giving their driver the means to do so.

We have also tried to show that for this issue – which moreover is becoming increasingly governed by regulations at national and international level – a sound design approach, i.e. an approach using restricted, mastered audible signal design, is a pertinent, effective solution from the point of view of both safety and ergonomics, and of acceptability and sound ecology.

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