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Do electric cars have to make noise? An emblematic opportunity for designing sounds and soundscapes

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Electric cars tend to become the emerging generation of automotive vehicles for the next decades. One of their main features is that they are rather silent and then present issues as: must electric cars be sonified for preventing pedestrians from dangers? If necessary, what kind of *sound signal* is to be put to fulfill safety rules without contributing to the environmental pollution ? Moreover, because the starting point of this thought is nearly a blank page, it opens a large field of experimentation on different aspects of sound design: innovative approaches to create sounds in interactive configurations, role of sound to convey functional informations, aesthetics qualities or even emotional feelings, etc.

In the frame of an industrial collaboration, we tried to handle these questions by examining the state-of-the-art in that domain, defining the specifications that sound has to comply with (warning for direction and speed, driver feedback of speed and functioning, various branding components, etc.), prototyping various ideas of interactive sonification, and initiating evaluation experiments especially in terms of primary functions (notification of presence and approaching speed). Some results from different steps of this work together with overall reflections and perspectives on the general topic will be presented and discussed.

Introduction

The present study deals globally with a new class of automotive vehicles called Quiet Vehicles (QV) including those exclusively propelled by an electric engine, called Electric Vehicle (EV) and those using an hybrid propulsion – electric or Internal Combustion Engine (ICE) –, called Hybrid Vehicles (HEV).

The fact is that, according to all the observers and actors on the field, EV/HEV will increasingly gain in importance for the next decades in our daily environment. Sandberg & al. [1] reported for instance that a leading european analyst has predicted that in the next 20-30 years “all cars will be electrified somehow” or that the Japanese Governement has announced its goal to overwhelmingly develop the electric car market until 2020 (cited in [2]).

The main specificity of the EV – and HEV in electric mode – is that they are completely *zero emission* regarding either gaz or sound emissions. Then, as well as having an impact on our daily environment in terms of air pollution (which is already non-negligeable, especially in a urban context), the introduction and growth of QV will also have a great influence on our daily sonic environment, or our daily *soundscape* with regards to Schafer’s terminology [3].

From that point of view, the consideration of advantages and drawbacks of the inherent quietness of QV seems to point out a certain divergence of opinion concerning the way to analyze it and the potential resulting actions to lead. For instance, on one hand, it is argued that tyre/road noise level is sufficient in many common traffic conditions for signifying the presence of the vehicle, so that there is not enough justifications for equipping quiet QV with extra artificial sounds (in [1]). On the other hand, a comparison shows that the frequency balance between the three main noise components (engine, wind, tyre/road) are more or less inversely distributed in loudness along an ERB scale [4] and then EV/HEV are so quiet – outside and inside – that they constitute a good opportunity to realize a dedicated sound design to face at the risk it can potentially represent: weak sonic presence for outside local agents around the vehicle, (pedestrians, cyclists, visually impaired people) and lack of interior feedback for the driver.

Nevertheless it is nowadays generally accepted that, compared to ICE vehicles, Quiet Vehicles don’t provide enough auditory cues either for its direct or indirect uses (drivers, pedestrians, bicyclists) and that there is a real need to build a sound signature for this kind of vehicles; as the Quiet Road Transport Vehicles (QRTV) United Nations working group officially mentioned in one of its reports: “*vehicles propelled in whole or in part by electric means, present a danger to pedestrians*” (cited in [1]).

On that basis, an industrial collaboration was initiated at the end of year 2009 between the french car manufacturer Renault and one of the Ircam’s scientific teams in order to develop a concept of sound signature for EV. From the industrial part, the project involved several departments of Renault: Product (vehicle program, services to client), Engineering (mechanics, electronics, acoustics) and Design. From the scientific and artistic part, the project was developed at Ircam within the Sound Perception and Design team in association with a composer / sound designer, Andrea Cera, who assumed the role of sound creation and production that tended to take a central part of the project. Structured around this *Conception* phase, the whole project was nevertheless inserted in a global common methodology comprising a pre-phase of *Analysis* and a post-phase of *Evaluation* involving a possible feedback on the proposed prototypes.

However, for sake of confidentiality, the content of the present paper will mainly focus on the methodology itself applied to generic propositions, and in case, will present intermediate and non-finalized propositions. The plan of the paper then follows this 3-step approach: 1-*Analysis*, including state-of-the-art, industrial specifications and context analysis; 2-*Conception*, including the sound synthesis environment and sound design propositions; 3-*Evaluation*, including either objective and subjective validation process. The paper ends with Perspectives and Conclusion sections that tends to deliver opened questions on this current and critical topic.

Analysis

State-of-the-art

Except in official reports coming from institutional organizations (UN, or national associations) or unofficial notes from manufacturers’ technological watching, there are rather a few number of scientific publications investigating the question of the use of sounds for Quiet Vehicles. However, this question can be extended to the more general following topic: the controlled insertion of a new interactive sounding object in a given environment – relevance, emergence, acceptance and annoyance issues.

The few sections below report some of the most recent papers that deals with this precise quest: which kind of sound is to be put in a QV with regards to an objective criterion of perceptibility [5, 6], and a subjective criterion of acceptability [7, 8] ?

Kerber & al. [5] proposed a quantitative prediction of perceptibility literally called « *perception-distance* » by comparing computed masked thresholds (with regards to a given background noise level) and measured vehicle's sound level along time – or vehicle's position. Assuming a 0.56 sec. average reaction time (also converted in position), a minimum distance of perception is then estimated. The model is perceptually validated on several vehicles, at various speeds: 80% of the calculated perception-distances are within the interquartile ranges of experimental data, especially at lower speeds. This result can be seen as a tool to design sound signature, maximized in terms of perceptibility but minimized in terms of overall sound level.

Menzel & al. [6] experimentaly studied the level of three possible warning sounds adjusted in four different background noises, presented in a laboratory environment. Two thresholds are measured by an adjustment procedure: *just audible* and *clearly detectable*. Results estimate a 15dB (at least) level difference between these two thresholds and show that they both strongly depends on the nature of either background noise or/and warning signals.

Wogalter & al. [7] undertook a large survey (380 persons) to explore interest and concerns about electrically powered cars. One of the main results is a collection of lexical suggestions and recommandations about sounds to implement in quiet vehicles: predominantly traditional engine or hum sounds (38%), and secondarily, music (14%), whistle (8%), beeps (5%), horns (5%), etc.

Nyeste & al. [8] conducted a preference study for sounds that might provide acceptable auditory cue to Quiet Vehicles. The study built a sound corpus from Wogalter's lexical results [7] on the basis of a 6-class typology: engine, hum, horn, siren, whistle and white noise. The soundfiles were played back with a video support and were evaluated on a semantic scale. Results points out two significantly different groups (engine, hum, white noise *vs.* horn, siren, whistle) and shows that engine sounds are the most preferred whereas horns are the least preferred.

Specifications

Several formatted and factual specifications coming from Renault were another departure point of the analysis work. These inputs came from the different departments involved in the project and formed the initial *brief* of the collaboration.

The Product department gave hints on the general and strategic context of this industrial challenge and drew a typology of different end-user (customer) categories. According to the result of internal customer surveys, it also gave elements on what is expected – and imagined – in the future concerning EV, its associated sounds and its environmental impact. Besides, the Customers Requirements department gave specifications on acoustic performances, functionalities regarding customer uses and and other several basic needs in terms of ergonomy and functionality (e.g., feedback for pedestrian)

The Design department delivered the fundamental ideas on which the EV project was based in terms of inspirations and concepts in order to develop sonic propositions that would be congruent with the other sensory aspects. These informations were transmitted in the form of qualitative recommandations (prototypic words, images, mood boards, etc.) regarding aesthetics but also brand relationship.

The Engineering department provided factual data concerning all the hardware components: electro-acoustic specifications (synthesizer, amplifier, loudspeaker), control parameters (i.e., which data coming from the vehicle could be used), dynamic ranges, etc.

Context analysis

A broader context analysis was also undertaken at the beginning of the work in order to collect the largest amount of data/ideas from any kind of directions – even if some of them would seem to be, at first sight, somewhat trivial – before starting to fix the first ideas in conception. This *extended state-of-the-art* led us to go mainly in two distinct directions: a look at empirical solutions (generally coming from cinematographic industry or craft/individual experiments), and the integration of Schafer's principles in terms of acoustical ecology [3], on the basis of a local environmental (urban) sound recording database.

Concerning how sound designers in science-fiction movies or cartoons imagined the sound of future vehicles, we found that, from *THX 1138* to *Gattaca*, from *Blade Runner* to the *The Jetsons*, continuous, drone-like sounds are used (jet engines, high frequency electric motor pads, swooshes of filtered noise, …). The fact that rythmic or periodic sounds were never found in that case was interpreted as the attempt to outline the non-mechanical nature of EV's engine and to distance from reminding of a traditional power unit's clicks, mechanics or strokes. Moreover, in that field, it is worth noticing that the caricatural nature of movie sound design tends to exaggerate evolution of dynamics, timber and pitch (e.g., a little acceleration, is often sonified with enormous quantities of timbral changes, or a huge glissando / big crescendo). Resulting from that first point, we draw a first guideline: to take movie's inspiration only on the timbral aspect, while designing dynamic and pitch with reference to a traditional thermic engine's behavior.

The reference to the seminal work of R.M. Schafer came from a strong will to apply an ecological paradigm to the design of the sound by trying, in particular, to develop the idea that sound events found in nature follow a hierarchy of time and frequency zones.

For that, we decided to study a self-recorded collection of urban soundscapes, in order to throw light on the fundamental question: which frequency zones are overcrowded and which ones are suitable to host the EV sound at low level ? As first results, we extrapolated few ground-rules that provide tangible starting points – but without being neither universal nor context-independent:

1. avoid sounds in the low frequency range (20-100 Hz), zone where urban soundscape is mostly polluted; to be heard in this range, a sound must be very loud.
2. have some energy around 1000 Hz, a frequency zone seemingly not too crowded.
3. create a clean, static, ordered sound able to emerge by its regularity from the ever changing soundscape.
4. assure detectability by having a dense and rich layer of sound at higher frequencies (around 3000 Hz.) but at a low intensity level; nevertheless, this layer has to be quite dense (for instance, swooshes of filtered / granulated white noise) in order to be differentiated from other traditional components emitting in the same frequency zone (e.g., squealing noise of trucks' brakes).

Conception

Sound synthesis engine implementing

The first part of the conception step consisted in defining the sound synthesis engine and implementing it in a software environment.

The functional definition is related to the four main components of the synthesis engine: the built-in data, the input and control parameters and the output rendering.

Data: sound buffers. The final synthesis engine is based on four mono variable-length sound channels, each one playing a soundfile in loop. The presence of four different length loops allows to create a living and ever changing sound, while a single loop would be perceived as too much mechanical and repetitive. Each channel is dedicated to a specific role: the first two are dedicated to medium/high frequency range (1-2 kHz) and contain the more characteristic elements, the ones that define the overall aesthetic of the sound. The third channel is dedicated to the lower frequencies (100-400 Hz.) while the fourth developed the "breath" component around 5 kHz. Another reason for using this 4-channel architecture concerns its relevance to interactive evolution of the sound.

Input: vehicle's speed. The behavior of the sound engine is controlled by the speed extrapolated from the RPM data sent every 10 ms. by the vehicle's electronic processor.

Control: gain and pitch levels. The vehicle's speed (from 0 km/h to 30 km/h) controls independently the level and the reading rate of the loops played by the four channels. In this way, some sound are present during the whole acceleration, some others emerge later or disappear before. The independence of the four channels also allows an easier workflow when performing the setup at different speeds: if just one of the four elements creates a resonance at, for instance, 15 km/h, it is possible to change the dynamics curve of this only element, leaving the overall sound consistent.

Output: sound mixture. The vehicle's speed controls not only the individual channels' volume, but also the overall (master) level of the sound sent to the output. The Engineering/Acoustic department involved in the project determined a mastering rule by calculating the difference between the noise of a traditional and an electric (silent) car and passing at different speeds.

A prototype implementation of the sound synthesis engine was developed in the Max/MSP environment (http://cycling74.com). This development used several generations of Max patches which progressively embodied changes and improvments in different contexts:

- to allow the dynamic comparison of different types of sounds; at given moments, the patch have had to allow a quick comparing of up to 30 different presets.
- to embed the changes in the processor architecture: from simplifications in the processing architecture, to limitations in memory space.
- to allow the listening of realistic and contextualized rendering of a current sound: via measurements (Impulse Response), addition of a series of modules for the modeling of the sound rendering device (loudspeaker) and of the in/out transfer function (resonances of the vehicle's parts where the loudspeaker will be mounted).

Sound design iterative definitions

The sound design process itself consisted in iterative steps of production on the basis of formalized ideas of the functional and formal (aesthetics) informations – previously delivered during the *brief* or following working sessions – and their mutual relationships able to point out theoretical rules for conception.

On the *functional* point of view, several functions have been described with regards to the two main functioning modes (stationed or on-the-go) and the differents agents able to be on the contact of the vehicle (essentially, pedestrians and drivers). Some of this functions can be summarized as follows:

- warning for presence for the pedestrian when EV is stationed or more probably on-the-go, at very low speed (below 5 km/h)
- warning for approach for the pedestrian when EV is on-the-go, at higher speed (between 5 and 30 km/h)
- informing for aesthetics (quality) for the pedestrian, when EV is either stationed or on-the-go
- warning for the speed for driver at rather high value (up to 30 km/h), as it has been proved for instance that the lack of sonic feedback leads to underestimation of the speed [9] or driving-task deterioration [10].

On the *formal* point of view, some structural components for sound have been identified in terms of *elementary unit properties* and *large-scale morphologies*. These components have been defined, worked and detailed within the working group, by all possible communications medias: lexical (words), graphical (images, sketches, drawings) or even aural (reference to similar sounds, musical excerpts).

Elementary unit properties gather components that describe either a spectral or temporal unit content and is associated to a sonic prototype; concepts like *layer*, *breath*, *clicking*, *high/low pitched*, *granulation*, *wind* progressively appeared on the workbench and constituted a sort of sound textures repertory available for conceiving the sound signature in its entirety.

Large-scale morphologies have then been built upon the elementary properties described above. These morphologies followed the dynamic profile of a vehicle's scenario: typically, start / acceleration / deceleration. Figure 1 shows symbols used for graphical description of two dedicated morphologies.

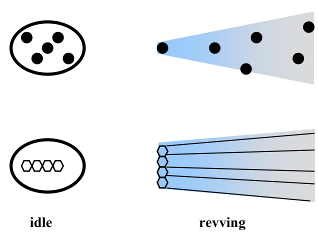

Figure 1: large-scale morphologies graphical depiction

Then, on the basis of background knowledge (especially, in psychoacoutics and aesthetics fields) and of informations collected during the *Analysis* phase and self-observations resulting from preliminary in-situ experiments, relationship between functional and formal elements have been established and iteratively tested along the time of the project. This functional/formal mapping represents the core of the conception phase that underlies the production of sounds and constitutes one important deliverable of the project (and is consequently under the project's confidentiality agreement).

Moreover, each iteration led to the drafting of a *sound space* containing a set of items (between 10 and 30, each time) tagged with axes defined with regards to functional and/or formal targets. One iteration was systematically the results of a listening/validation/selection process included in a feedback loop with the industrial partner.

Evaluation

After a certain number of run inside this loop, one *sound space* iteration have been fixed (12 items). On the basis of this configuration, included in the industrial development course, a first step of laboratory (*in vitro)* acoustical and perceptual validation have been undertaken.

Output of these tests provided arguments and data to go back in conception, in order to improve the initial propositions and to reduce the number of items finally retained (3-item specified target). Afterwards – following the industrial course progression – a second step of acoustical and perceptual validation have been made possible on the EV itself (*in vivo*).

For confidentiality reasons (the ones that currently prevent from presenting the finalized propositions, precisely concerned by these last *in vivo* evaluations), this section only deals with methodology and partial results of the first step of validation about the 12-item *sound space* fixed at mid-term level of the project.

Acoustical: spectral emergence

On the acoustical point of view, the evaluation of the proposed items consisted in a relative comparison between urban noise spectral characteristics and spectral contents of the proposed solutions. Therefore, PSD estimates – Power Spectral Density by Welch's method (run in Matlab) – of urban noise recordings made at the beginning of the projet (see section 2.3) were computed and compared to the PSD of a continuous sound sequence of the proposed solutions (linear evolutions between 0 and 30 km/h). Results were analyzed qualitatively on the basis of graphical observations and allowed to make some hypothesis about the behaviour of each propositions when immersed in a given urban soundscape (see Figure 2, for two items)

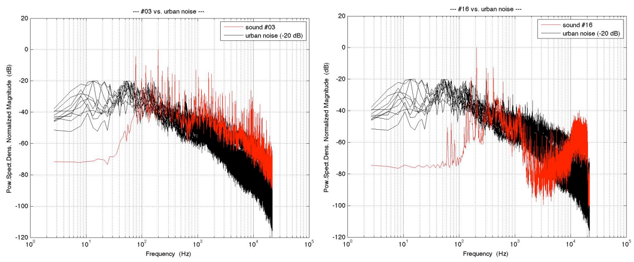

Figure 2: relative emergence for sound #03 (left) and #16 (right) – (x-axis: Hz, in log-scale; y-axis: relative dB)

At that point, it is worth noticing that Shafer's acoustic ecology guidelines initially stated in the *Analysis* part (section 2.3) don't seem to be completely respected. For instance, low frequency components (20-100 Hz) should have been especially limited because urban noises usually get a lot of energy in that range. One main reason for stretching these rules is a pragmatic compromise between theoretical concepts and practical specifications that forced the sound to be, for instance, "like a traditional engine" as it is quoted in Wogalter's survey [7] or rated as "the most preferred" in Nyeste's experiment [8] (see section 2.1 for more details on these results).

Perceptual: listening test

On the perceptual point of view, the experimental approach tended to verify hypothesis concerning two main functions, in that case intentionaly focused on the pedestrian position: *presence* and *approach*. The questions that the perceptual evaluation have tried to answer were then: is a given sound able to specify the EV existence in a (quasi-)static or approaching situation ?

The experimental set-up used an audio-video presentation. The visual content was composed by a unique video showing a car (with neutral appearance) in both situations: acceleration from a stationed position, for *presence*, and continuous speed driving, for *approach*. The audio content was composed by a unique background soundtrack (noise from natural environment, tyre/road, etc.) and by a variable foreground soundtrack corresponding to the given experimental condition (*presence* or *approach*) and each sound design proposition.

The experiment took place in a sound-isolation booth equipped with an Apple PowerMac Intel DualCore, RME Firefece800 audio interface, Yamaha MSP5 pair of loudspeakers and 27" Samsung LED screen. Nine among the twelve intermediately selected items were inserted in the corpus (S1 to S9), where a tenth sound coming from a traditionnal ICE was added (S10). The two qualitative variables:

- faculty of *presence* signification,
- faculty of *approaching* signification

were evaluated by participants on a semantic differential scale coded from "doesn't signify at all" (0) to "perfectly signify" (1). An illustration of the test interface is given in Figure 3. The test was done twice in a double random procedure (sounds and variables orders) by 30 participants. The output data were two 20x30 matrices corresponding to the score of signification faculty for both *presence* and *approach*.

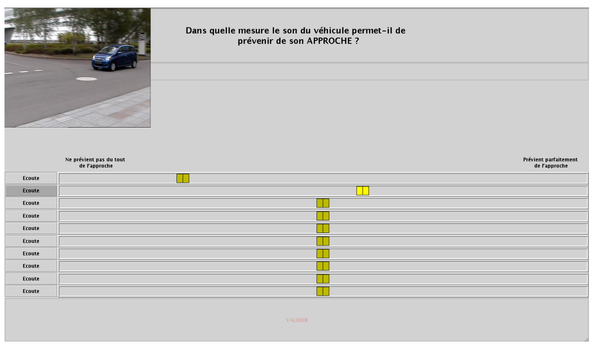

Figure 3: test interface for *approach* experiment

An ANOVA analysis showed globally significant difference among sounds with regards to both variables. Concerning *presence*, two groups of sounds (4 sounds vs. 6 sounds including S10) could have been discrimated; the 4-sound group (S1, 3, 4, 6) getting significantly higher score of presence faculty than the others. Concerning *approach*, the results are less distinct: one sound (S9) seems to get significantly higher score, another sound (S10) seems to get significantly lower score, meanwhile the remaining others get average scores (around 0.5). Figure 4 shows the graphical results of ANOVAs.

Figure 4: ANOVA interaction plots between sounds and score of *presence* (left) / *approach* (right)

At that point, it is again worth insisting on the fact that these intermediate results were used for a second conception and validation run in order to improve the initial propositions (12 reduced to 9) and to converge to 3 final propositions, in a second step. Thus, the results showed in this section must be taken as generic data rather than ground-truth with regards to the global aim of the project.

Perspectives

Within this framework, two time scales of perspectives can be considered.

In a short-term, the goal would be to follow the industrial implementation. Actually, the transfer from prototype to mass-production is also a part of the project's challenge, and it seems important to control as much as possible this last step of the process that should not become the weak (missing) link, at the risk of damaging the entire work. For instance, porting Max/MSP prototyped patches to embedded devices (e.g. EEPROM) has constituted a non-negligeable phase of the post-production work and has even involved some adjustments of the initial content.

In a mid-term, taking advantages of the fruitful laboratory of ideas this collaboration offered and considering this achieved attempt as a first step in the resolution of the main issue, a future goal may be to enlarge the scope of the work in wider collaboration contexts in order to bring global answers to questions that emerging Quiet Vehicles will certainly raise in the future.

5 Conclusion

The growing issue of quietness of Electric Vehicle (EV) or Hybrid Electric Vehicle (HEV) has been treated in this paper within the scope of an industrial collaboration between a car manufacturer (Renault) and a research team in sound perception and design (Ircam/SPD) associated to a composer / sound designer (A. Cera).

For sake of an ongoing confidentiality agreement, the current paper has only been able to present the methodological approach used to deal with this problem and some intermediate results that are only partially related to the industrially implemented solution that still undergoes final developments.

Nevertheless, the paper aimed to present tangible elements of work with regards to the three main part of the global project: *Analysis* with a selective literature review, a context documentation and several views of industrial specifications of the matter; *Conception* with the definition of the sound design approach in terms of tools, concepts and procedures; *Validation* with the presentation of partial protocols and results either in the acoustical and perceptual field.

Afterwards, short-term and mid-term perspectives are infered from this work, and widely, from the general topic of sound for Quiet Vehicles that tends to gain in importance in the next future.

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