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Sound signature of Quiet Vehicles: state of the art and experience feedbacks

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ABSTRACT

It seems now widely conceded that *Quiet Vehicles* are actually too quiet for leaving out the crucial question of their sound signature. When considering the increasing volume of works in that domain, it looks obvious that a dedicated sound design approach for these new means of transport becomes fully relevant regarding security (for people around) or ergonomics (for people inside). For quite a long time, and among other labs, the Sound Perception and Design (SPD) team at Ircam has focused a part of its works on that topic which represents an emblematic framework to operate knowledge, methodologies or tools developed in the field of Sonic Interaction Design. The paper aims at presenting, first, an overview of recent scientific studies in that field together with a review of current legislations or standards that are – or tend to be – effective in several countries. In a second part, we will try to adress this issue in the light of several works achieved within SPD team, especially some parts of a long run collaboration with a french car manufacturer, but also more recent investigations that contribute to the general question : what is the best sound for a quiet vehicle ?

Keywords: Quiet vehicle, sound design, state-of-the-art

1. INTRODUCTION

The silence of electric vehicles: blessing or curse ? This question asked by Cocron & al. in a recent paper [1] (and recovered from a previous idea expressed by Otto [2]) defines quite well the ambiguity involved by the emergence of this new type of motorisation leading to another generation of means of transport called *Electric Vehicles* (EV) or, by extension, *Quiet Vehicles* (QV). In fact, this is a blessing for acoustic ecology, sonic environment and soundscape thanks to QV's zero (sound-)emission property; but, in the same time, this can be a curse for security, ergonomics, and human-centered activities because of this same QV's zero (sound-)emission property.

In more details, and considering in priority a urban or peri-urban context, this issue is first introduced with regards to the coexistence of quiet vehicles with other vehicles powered in a more traditional manner (namely, ICE – Internal Combustion Engine). This situation induces potential risks for people evolving in their close vicinity: pedestrians, cyclists, but also, and undoubtedly, visually impaired persons who use auditory informations for localization, navigation and obstacles/dangers identification. Moreover, and more indirectly, this issue is also adressed in the inner of the vehicle, in terms of ergonomics and driver's – or passengers' – usage, to the extent that senses of driving, and especially speed perception, are not informed at all by the "natural" acoustic feedback provided by a traditional ICE. Finally, this issue can again be expressed in a larger frame,

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with regards to the acoustic ecology field, by considering the way in which the introduction of this new – moving, and potentially silent – object in the current environment can durably modify and shape the sound of cities and landscapes for the next decades.

Based on this first degree of analysis, open questions on this topic can be formulated as follows: should one give a sound, or a sound signature, to quiet vehicles ? In case, should it be conceived more as a warning (alarm) or resulting from a dedicated sound design process ? Which properties should this signal get in order to, first, fulfill minimum safety rules, second, answer to functional and ergonomic requests (emergence, distinction, understanding, interpretation, etc.), and third, not contribute to a general increase of sound level and pollution ? How can this approach be compatible with acceptability and integration criteria ? And finally, in a nutshell, what could be the *best sound* that a quiet vehicle should emit in the future ?

Since the very end of the 90's a growing number of scientific studies have focused on the question of EV with different points of view: measuring the impact of the QV in terms of detectability, modeling the presence of EV's in a given background noise, or proposing (and testing) sonic solutions for additional sounds or warnings. In a larger frame, national or international collaborative research projects have started to be initiated in different countries: for instance, European FP7 eVADER[3] which focuses both on external and internal sound signature [3] or French ANR Metason[4] which includes a section dedicated to the driving auditory feedback delivered by quiet vehicles [4]. Moreover, at a political level, national or international regulations have been discussed and implemented with a certain number of functional and technical recommendations: for instance, the United Nations *Quiet Road Transport Vehicle* (QRTV) working group [5], the *National Highway Traffic Safety Administration* (NHTSA) in the United States [6], the *Japan Automobile Standards Internationalization Center* (JASIC) in Japan [7] or the recent European Parliament draft legislation which specifies – within a directive about automotive noise limits – a "compulsory requirements in future to add sound to hybrid and electric vehicles" [8].

Considering this question as an emblematic frame for sound design especially because of its societal impact, the Ircam / Sound Perception and Design team (SPD) started to contribute to this reflection since the end of last decade with, first, an applied project that aimed to realise a specific EV's sound signature, and then, further attempts to formalize the main aspects of this problem and draw a general research framework on that topic. In fact, the team started from a singular study, in collaboration with a french car manufacturer (Renault), that gave the opportunity to apply a defined methodology mixing scientific *knowledge* and artistic *know-how* assumed by a composer / sound designer. Then, extending this applied approach to more general questions, a preliminary study was initiated two years later; it investigated the role of basic sound properties (temporal and spectral) in the ability to detect Quiet Vehicles immerged in urban environments. Finally, in the course of several recent collaborative project submissions, a general research framework around the issue of EV's quietness has been outlined; it tries to identify a large number of key points and propose an overview of research fields attached to this problematic.

The present paper is then organized in two main parts: i/ a selective state of the art structured by the above-mentioned categories (measurement, modeling, proposition) and especially focused on eligible sound properties specifications; ii/ a contribution from Ircam/SPD team in terms of experience feedbacks, preliminary overall results and formalized ideas.

2. STATE OF THE ART

This section does not claim to present a complete and exhaustive state of the art, as an increasing number of studies and reports has been published on this topic since the previous decade (for instance, first published US patents of an "Apparatus generating noise sound for electric car" [9] or a "Simulated sound generator for electric vehicles" [10] date back to end of the 90's).

Bibliograpic data quoted in this section tend to be structured in a way to differentiate three kinds of study conducted in different directions: 1/ <u>measurement</u> of the impact of EV with regards to ICE or different background noises, implying several experimental paradigms (in laboratory / in situ, from the inside -driver / outside -pedestrian point of view, silent / sonified EVs, presence / direction / speed detection, etc.); 2/ <u>modeling</u> of the insertion of a vehicle in a given environment with regards to the sound produced and on the basis of perceptual auditory models, leading to an estimation of

[3] http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=12164659
[4] http://metason.cnrs-mrs.fr

the perception distance for each condition (vehicle + background); 3/ proposals (and evaluation) of specific warnings or designed sounds in terms of spectral properties, temporal morphologies and interactivity parameters attached to the functioning of the vehicle or to environmental variables (automatic detection, active control, etc.); in this paragraph, non-acoustical solutions are also listed (haptic, behavioral, etc.).

Moreover, this section tries to highlight the selected papers on future objectives and perspectives, i.e. tries to extract in each study's what is found as limitations or elements for further investigations. Finally, this section is also not exhaustive as much as being a complement of other scientific works mentionned and detailed in previous publications of the authors ([11], [12]).

2.1 Measurement

2.1.1 From the outside (pedestrian) point of view

Ashmead & al. [13] undertook a detection study focused on vehicle paths – instead of detecting vehicle start, presence or direction, as it is generally done in other studies. Quoting that "pedestrian risk from turning vehicles is an important category of injuries" the study focuses on motion paths relevant to pedestrian activity and especially examined the ability to distinguish between *straight* and *turning* paths, in order to guarantee the safe crossing for people who use or need auditory cues to cross the streets (namely, visually impaired). The study rested upon an acoustic simulation apparatus that simulates in laboratory these two given paths with two specific sound signatures taken from recordings of: i/ a traditional gasoline engine idling; ii/ a proprietary electrical sound (woosh / hum characteristic, with low pitch thread and higher pitch tonal components). Moreover, because of experimental constraints, it is mentionned that interactive audio features – e.g., covariation of spectral composition with vehicle's speed – are not taken into account in the simulation procedure. The main experimental factor is the sound level emitted either by the vehicle or the background and consequently the signal to noise (SNR) ratio between these two components. Three experiments are achieved by a reduced panel (between 4 and 8 participants) with normal vision and hearing: 1/ detection of straight/turning paths in an *extremely quiet background* (anechoic chamber) with two different levels of emitted sounds; 2/ detection of straight/turning paths in several backgrounds with different overall sound levels (*quiet*, *residential*, *moderate traffic*, *busy traffic*); 3/ adjustment of the sound level emitted by the vehicles to make the distinction between straight/turning paths in a fixed given background (*moderate*). General results show that listeners used sound level cues to detect a particular path, and surprisingly that, in a moderately noisy background (expe. #3), the SNR threshold needs to be higher for a gasoline than for an electric vehicle. However, this conclusion is moderated by the fact that "electric vehicle sound was more distinct spectrally from the background traffic noise". Beside, in a more global conclusion, the study assumes that "auditory motion perception has multiple perceptual components" and that it will be "valuable in future work to explore these factors".

Emerson & al. [14] started with the assumption that "auditory motion perception has not been thoroughly investigated" to undertake a similar study concerning detection and discrimination of typical vehicle paths. The study includes two experiments respectively related to typical crossing conditions: 1/ detection of a traffic gap in a straight two lane road with constantly passing-by vehicles – equivalent to adequate time for crossing the lane; 2/ detection of traffic surge in the parallel road of a two one-way street intersection – equivalent to safe crossing (red traffic light) for pedestrian in the perpendicular way. Experiments took place in real situations with a fleet of hybrid electric vehicles (HEV) from different makes and models and involved a mix of blind and sighted participants. Experimental measured factors were speed, sound level and frequency spectrum of each passing vehicles. The main global findings are as follows: at low speeds (< 20 mph) ICE and HEV models were equally detected, but at higher speed or from a stop position, some HEV models are less detectable than ICE. This being, apart from assuming that "these results cannot be universally applied", the study points also out that "spectral composition of the vehicle sounds might be a component of detectability" and, moreover, that the detectability issue may also involve "attentional factors, how the sound appears, or momentary fluctuation of the vehicle shape".

Garay-Vega & al. [15] realised a study dealing with auditory detectability of HEV both in conventional conditions (approach, backward) and in a turning perception paradigm. Thus, three specific maneuvers are considered (approach at constant speed, backing out and moving in parallel and slowing) together with two typical background environments (*residential* and *suburban*). The experiment implemented binaural recordings of each of the scenario (maneuver + background) built upon recordings of 4 vehicles (2 HEV in electric mode and their similar ICE models) and involved around 50 legally blind participants. The experimental factor was mainly the sound level (L_{Aeq}) emitted by each vehicle and the measured experimental variables were related to detectability performance (reaction time and missed detection frequency). In one of the experimental configuration (response time when vehicles are moving in parallel and slowing), a counterintuitive result shows that HEVs are detected sooner than ICEs but is explained by the presence of a specific tone emitted by HEVs and associated with "the electronic components of the vehicles when braking (regenerative braking)". Otherwise, global findings of the study can be summarized in the fact that "HEVs operated in electric mode are not as detectable as their ICE counterparts in some scenarios" and that "response time for each vehicle maneuver depends on ambient sound level and vehicle type". The study concludes again that "sound content, such as relative proportions of high and low frequencies, can be manipulated to improve the effectiveness of such alert sounds while reducing the overall community noise impact".

Goodes & al. [16] carried out a detection study about quiet vehicles with blind volunteers (27 persons). The study involved a dedicated vehicle equipped with a specific embedded audio system delivering alternatively: i/ a typical diesel engine noise; ii/ a typical diesel engine noise altered with a bell like tone; iii/ no noise at all. The experiment consisted in a standard pass-by test in a parking lot and the measured variable was a distance from which the vehicle started to be heard by each member of the jury. The experimental factors tested were both the speed range in which the additional warning sound system should be applied and the positionning of the loudspeakers together with their directivity characteristics. The study concludes that an additional sound system should be controlled in radiation pattern in order to focus the warning signal only to the concerned persons, reducing as much as possible its impact on the overall sound level.

Dudenhöffer & Hause [17] investigate the question of acoustic warning systems of electric vehicles within the framework of a task force of the Economic Commission for Europe (UN/ECE). On the statement that "the lack of subjective perception leads to wrong conclusions", the study focused on acoustic perception of electric cars below 30 km/h in realistic conditions with a panel of visually impaired waiting at a roadside and who are asked to cross the street after the passing of each test vehicle. The pool of tested vehicles was composed of a mix of eleven actual HEV and ICE vehicles. For each passing and participant, a semantic differential protocol about sound characteristics was implemented (questionnaire) and an objective "time-to-vehicle-arrival" measurement was operated via an external remote button. Experimental factors were sound levels and speeds of vehicles (from 10 to 40 km/h). Main results show that, either in terms of sound level or subjective perception, differences between HEV and modern ICE vehicles are "less than expected" or not significative at all. General conclusions of the study are then that "all (modern) quiet vehicles regardless of their mode of driving, should have to be adjusted and emit artificial sounds" but also that "a better solution to accomplish higher safety should be based on an intelligent electronic assistant system, not on a warning sound system".

2.1.2 From the inside (driver) point of view

Cocron & al. [1] examined the issue of EV/HEV's low noise emission from the drivers' perspective and experience. The large-scale experiment consisted in parsing a group of 40 drivers of an electrified vehicle (with no additional sound) during a 6-month period. For this given study, the focus was put on how drivers handle the issue of "implications for traffic", i.e. which role does the low noise emission of EVs play in the user's experience of driving and in the relations between automobiles and pedestrians. The experiment was conducted by mean of interviews and questionnaires at three particular times of the test : i/ at the vehicle handover (T0); ii/ after 3 months (T3); iii/ at the end of the experiment (T6). Main findings of the study can be summarized as follows: "expected substantial problems due to the lack of noise" have finally resulted in only few incidents. In fact, drivers "quickly learned to identify the situations which might be crucial", "increased attention in parking lots, quiet streets and during parking maneuvers" and were "continuoulsy thinking ahead" while driving. Then, conclusions of the study claim for both behavioral and technical approaches to face the QV issue: on one hand, special drivers training for EV/HEV should be a possible solution, and on the other hand, even if low noise emissions have been mentionned as "one of the biggest advantage of EVs", if an external sound is to be implemented, it should be depending on the speed of the vehicle.

Hoogeven [18] took the same approach as Cocron & al. [1] to investigate the QV problem. A questionnaire dedicated to EV's users was implemented and posted online. The aim of this survey was mainly giving an answer to research questions such as “sound produced by EVs”, “potential dangerous traffic situations”, “behavioral changes while driving EVs”, “possible suggestions for safety improvements”, etc. Some of the main results are that a quite large part of the participants (36%) estimates that EVs are safe and nothing “has to change at all”, as most of participants (69%) “changed their driving behavior when driving an EV instead of an ICE vehicle”. Considering behavioral aspects, data collected during the experiment claim also for a change of behavior 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 larger amount of persons (19% vs. 13%) would prefer a “warning sound” than a “driving sound”; the former being judged sufficient enough and less environmentally intrusive with regards to overal noise pollution and annoyance.

2.2 Modeling the perception of vehicle-background condition

Kerber [19] and Kerber & Fastl [20] investigate the role of exterior noise level in collision avoidance scenario and proposed a numerical model for quantitative prediction of perceptibility (named “perception-distance”). The experimental measurement of reaction time to vehicle external noise was conducted in a laboratory condition and involved a looped background noise (“babbles of voices” in an outside environment) and six recorded pass-by sounds (2 vehicles – diesel and gasoline – at 3 constant speeds). Data collected are used to build a model for critical distance estimation implemented by comparing computed masked thresholds, with regards to a given background noise level (curve 1), and measured vehicle’s sound level along time – or vehicle’s position (curve 2). The considered weighting-function, physically measured on several cars and approximated by a logarithmic model, corresponds to the level of an approaching vehicle from 35 m. on the left of the listener to 0 m. – i.e. when the car is passing in front of the listener – and is assumed to be symmetric. The intersection point between the two curves and the integration of a pedestrian average reaction time (0.56 sec.) allow to predict the perceptibility distance of the vehicle approaching to a pedestrian position. Listening test conducted with different passing-by vehicle speeds have validated this model, especially for slow driving.

2.3 Proposals

2.3.1 Acoustical solutions

Owen [21] developed an applicative research to give a pragmatic and feasible answer adressed to EV’s quietness issue. On the basis of detailed technological solutions, his work proposes a dual approach for “both quiet cars adapting to visually impaired pedestrians and vice versa”. From the vehicle point of view – and apart from the data transmission part –, the retained option is based on the emission of a car-like sound. For that, a sound synthesis application is developed on the principle of a “blending of pre-recorded engine sounds at different engine speeds”. As far as the procedure is detailed in the paper, the sound production seems to be based on a signal decomposition (FFT analysis) of engine sounds at different speeds and a real-time processing of the output signal depending on speed value. A double-buffer synthesis method is also implemented in order to make an “accurate sound reproduction without interruptions”. A pilot testing was conducted with a very few number of people (N=2) and showed that it is “difficult for subjects to accurately determine the speed of a car’s engine based on the sound which it makes” and that no resolution beyond fast / medium / low speed can be reasonably achieved.

Tabata & al. [22] developed the Approaching Vehicle Sound for Pedestrians (VSP) concept within the frame of work-in progress regulations that are discussed worldwide (Japan, USA, Europe, China, etc.), together with an industrial development supported by a japanese automotive manufacturer (Nissan). This prototype is trying to rise three main challenges: detectability for pedestrians, quiet environment for drivers and also neighborhoods. The main sound properties are based on QRTV’s GTR recommendations [23]; three distinctive frequency regions are defined with regards to: i/ ear frequency sensitivity (2 – 5 kHz); ii/ hearing loss due to aging – presbycusis – (below 1 kHz); iii/ ambient noise characteristic frequency (around 1 kHz). Thus, a template of a prototype signal gets “twin peaks” respectively at 0.6 kHz, 2.5 kHz and “one dip” at 1 kHz. In the time domain, the sound morphology has also some specific properties: a “subtle modulation” of the lowest frequency peak (0.6 kHz) and a “pitch proportional to vehicle speed”; moreover, the VSP doesn’t work at idle and an “emphasized taking-off sound” is also implemented in order to maximise the surge detection by pedestrians. From this template, different versions of VSP were synthesized and perceptually tested with regards to the general specifications mentionned above (especially detectability vs. cabin quietness). The sound volume was set at a given SPL level (55 dB-A) with regards to level emitted by several ICE vehicles, listening test in laboratory and real world conditions. Main conclusions of the study are that the Quiet Vehicles issue is "more complicated than just adding a sound effect or artificial engine noise to electric vehicles" and that detection technologies concerning pedestrians, ambient noise, blind corners etc. should complement the approach in order to make an efficient active system.

2.3.2 Non-acoustical solutions

Sandberg [24] claims in his work that a "number of non acoustical ways to alert pedestrians" exists and will be "more beneficial to human health and safety" as it reduces "the maximum noise of vehicles instead of increasing the minimum noise of them". In fact, the main scope of the study argues that: i/ quietness issue is not really new and not especially attached to the emerging EV era (cf. Segways, electric bicycles, scooters or motorcycles); ii/ a lot of people chooses to "neglect sound cues" (cf. distractions by texting or listening to MP3 players); iii/ it looks "strange" that efforts are only made to "add noise to the lower levels instead of reducing the higher levels of noise"; iv/ it would be better to "reduce the higher noise levels, in order to reduce the masking effect". From this point of view, the study specifies a certain number of non-acoustical or even "soft" acoustical solutions: a punctual warning sound using a soft horn and more preferably non acoustic technological approaches such as autonomous braking system, pedestrian detection devices (combined with a radar) or even outside airbags dedicated to pedestrians as newly developped by some innovative brands. Above all, the study argues that this is the driver who finally has to take care of the vicinity of his vehicle – especially if it is notably quiet – and that all the aiding systems will have a counterproductive effect of "transfer of responsibility" and will encourage the driver not to be as aware as he should be, when driving a silent car equipped with a warning signal.

Owen [21] in his dual approach between quiet car and visually impaired (cf. section above) gets also the vulnerable road users' point of view and proposes an attempt to encode traffic information into vibratory feedback. The application aimed at being developed in personal mobile devices (e.g. smartphones) and uses a traditionnal Bluetooth technology for communicating with surrounding vehicles. The encoding principle is based on width modulation of single pulses to indicate presence and speed of vehicles; each pulse representing respectively one, two or up to two vehicles. This haptic approach seems quite promising as the pilot testing shows encouraging results with regards to the ability for users to count the number of cars – and even if these same results were more mitigated as for the evaluation of car speeds. However, a perspective of this approach may also be that the system can be coupled with audio feedback in order to facilitate the training of information coding, as it is yet done in other fields of CHI – Computer-Human Interaction (cf. HAID – Haptic and Audio Interaction Design conferences on this topic).

3. Ircam / Sound Perception and Design team contribution

Since sound design has been introduced in the Ircam scientific department (by Louis Dandrel, at the end of the 90's), the question of electric vehicle sound signature has straightaway appeared to be a promising field of research and application (cf. part of the work on PSA Peugeot-Citroen innovative project called TULIP – *Transport Urbain LIbre et Public* [25]).

More than ten years after this first attempt, the Sound Perception and Design team (SPD) has been involved in a large scale applied project concerning an EV sound signature for the french car manufacturer Renault. The mainstream of the project was concerning one model of the electric segment of the brand and started quite early in the industrial process so that a lot of specifications have been able to be considered either in terms of design conception, brand identity or technical constraints. This collaboration was also the opportunity to roll out a scientific/artistic articulated methodology defined for some years within the team, which involves analysis and evaluation scientific approaches together with a more intuitive creation phase generally assumed by a *sound-expert* (composer or/and sound designer) [26].

This project led to an effective – and industrially implemented – sound design realisation but also to opening questions about the issue of EV's quietness. From this acquired singular experience, more general questions and hypothesis have arisen and started to be studied in *beyond-application* works. This inductive -type path (from the specific to the general) recently resulted in an attempt to define a formalized framework for this topic trying to point out all the different components that should be *a priori* taken into account in order to give strongly argued answers to EV's quietness problematic.

3.1 Experimental approach: industrial collaboration

The first noticeable contribution of Ircam / SPD research team in the scope ot EV's quietness issue was done by means of an applied and experimental study deployed in an industrial scale with the french car manufacturer Renault. The aim of this project was to develop a specific sound design approach for one model of the EV segment of that brand – namely, *Zoe*. This framework gave us the opportunity to develop the methodology in use in the team, involving both scientific analysis and validation phases, articulated around a central artistic creation step, assumed in that case by the composer / sound designer Andrea Cera[5]. During two years (from 2010), the work has been developed according to a central axis focused on this given model, plus additional extra works relied on several *concept-cars*. It was composed of, first, an analysis of existing solutions at that time together with an extended bibliographic study of the domain, in order to define founding principles and inspiration guidelines. Moreover, the work had to integrate numerous specifications coming from different departments of the industrial process (*Design*, *Product*, *Engineering*). All of this resulted in a first round of sonic mockups taking into account these contraints and especially the interactive and real-time dimensions of the problem. Then, a validation step of the first proposals was conducted either in terms of functionality (ability to specifiy presence, approach or speed) and aesthetics (coherence with brand/model values and identity). After which, a second part of prototyping led to a finalized version in terms of three variations of a multi-layered basic scheme containing drone-like components with high frequency events, and which interactive evolution has been thoroughly designed in the span of 0 – 30 km/h. Finally, a ultimate porting step was assumed and operated the prototype transposition towards the digital / analogic platform (resp., chipset and loudspeaker) planned to be embedded in the vehicle itself. The final result is the industrial solution equipping the current, and commercialized, model (see [11] for further explanations and details).

3.2 Preliminary study in a larger frame

Behind this work, on the basis of the experience acquired during the industrial collaboration and following an inductive path to replace this question in a more general and theoretical framework, a preliminary study on the the detectability of EV was consequently conducted. In this work, two main questions were investigated: 1/ the influence of sound properties on the perception of presence and speed of a moving source; 2/ the description of EV's usage significative urban sound scenes as a corollary of a typological definition of urban environments. The study started by making hypothesis on the most expected factors for EV detectability in urban context. For that, a 3-state description of basic acoustic properties in the time-frequency domain was adopted: respectively, *continuous*, *modulated*, or *burst* temporal morphologies and *harmonic*, *inharmonic* or *noise-like* spectral contents. These hypothesis were experimentally validated by a listening test involving background noises recordings, sound signature synthesis (on behalf of the above mentioned categories) and passing-by scenario simulations. This test was designed for measuring reaction times to event detection. Main results show some areas in the time-frequency domain where detectability and emergence of sound signatures are not optimum. Moreover, additional results point out a significative learning effect (decreasing reaction time values along the 4-block course of the experimental protocol, whatever the signal and the background) and seems to be a promising way of investigating the question in a near future (see [12] for further explanations and details).

3.3 General framework

Further to the preliminary study, a general framework on EV's quietness issue is tried to be outlined in order to bring together and, if need be, to structure the research questions and applications attached to this topic. Then, the aim of this formalized approach is to try to develop a research program that will be able to give <u>generic</u>, <u>valid</u> and <u>working</u> answers to this question.

More precisely, the general objective of these guidelines is to define, as broadly as possible, the properties of EV's signature so that it will be optimized with regards to most of the identified criteria: the main functionalities it has to convey, the object (i.e. automotive vehicle) it has to embody, its ability to emerge from several environments in which it will manoeuvre, its ability to prevent from damaging or pollution of these same several environments, its ability to be integrated and understood by any population of users or agents, its technical operability and industrial operationality, its degree of interactivity with the concerned object and surrounding environments.

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3.3.1 Genericity

The notion of genericity is related to the fact that the question of EV's signature can be replaced in an extended usage context and can be explicited in a more global scope in terms of controlled insertion of a (sonic) interactive object in a given environment. Then, this implies general problems, such as:

- the relevance of specified sound qualities. In fact, several sound qualities – or timbres – can be considered and determine different formal or aesthetical aspects going from abstraction (see *earcons* in [27, 28]) to metaphor (see *auditory icons* in [29]). These fundamentals notions have to be integrated especially when considering the relationship between sound and function, but also between sound and associated object.

- the emergence, in terms of sound signaling (or signage). Acoustics or psychoacoustics properties of sound signals can promote emergence or, on the contrary, masking effects. On an another level, phenomens like flux segregation or sound source localization – getting into the Auditory Scene Analysis (ASA) research field – largely depend on properties of the signal, the sound source or the background noise [30, 31].

- the acceptability of the suggested innovation. The subjective judgment of a sound, especially in terms of preference or satisfaction, also play an important role in the information integration and its acceptance inside a daily sound environement.

- the noise annoyance generated by solutions. On the basis of Schafer's principle in the acoustic ecology field [32], the sound environment can be seen as an ecosystem where all the sources coexist. The introduction of a new sound source *species* must then ideally follow some rules that prevent from the increase of overall sound level.

3.3.2 Validity

The notion of validity is served by a methodological scientific approach that guarantees the consideration of a large number of factors able to influence the results, such as:

- contextual factors. Diversity of immersive environments in terms of nature (urban, peri-urban, etc.) or time evolving behavior. This point requires to define a typology of the considered spaces, to be found in the literature (for instance, [33]) and completed by additional studies in order to characterize them and relate their acoustic properties to those of the sound signature.

- human factors. Diversity of the targeted populations in terms of physiological or motor faculties with regards essentially to users' age. The important inter-individual difference that can take place when auditory perception mechanisms are involved led to consider several representative types of population (elderly, children, visually impaired, deaf or partially deaf people, etc.).

3.3.3 Workability

The notion of workability is motivated by the fact that this research topic is inherently developed in an applicative frame, and then has to take into account all the constraints related to the integration of potential solutions, depending on different fields, such as:

- sound production. In absolute terms, solutions can be of analog (mechanical / acoustical) or digital nature. In the latter case, numerous sound synthesis techniques are likely to be used (wavetable, additive, subtractive, modulation, granular, etc.) and the embedded electronic components must be compatible with the requirements of a given technique in terms of hardware and software architectures.

- sound diffusion. The audio chain (from source to loudspeaker(s) and until users' ears) gets a critical importance in the processing of the solution and, in this respect, must be optimized according to either electroacoustic criteria (power, efficiency, acoustic transfer functions, etc.) or industrial constraints (volume, feasibility, cost, etc.).

- *internal* interactivity. State variables of the vehicle (speed, acceleration, engine load, etc.) are the control parameters of the system and, thus, represent the degrees of freedom in terms of interactivity with the vehicle.

- *external* interactivity. Interaction modalities with outside surrounding environments on the basis of different kinds of sensor (presence, distance, temperature, sound level, etc.) can be imagined in order to make the system more proactive – and not only reactive. This point can also be relevant with regards to crucial questions like interaction efficiency or sound signature permanency, able to potentially generate tiredness or rejection phenomena.

4. CONCLUSIONS

The present paper tries to adress the identified Quiet Vehicle issue in the light of a structured state of the art together with formalized reflections on that topic, based on a previous applied experience and a preliminary study investigating general hypothesis about the influence of spectro-temporal properties of sound on QV detectability.

The state of the art points out, first, some divergences in the way to deal with the problem: the range of arguments goes from warning signals or designed sounds to non-acoustical concepts favoring behavioral or technological solutions. In the case of added artificial sounds, sound level appears to be a major cue for fulfilling basic functional requirements such as detection or pathway identification; but, sound level proves also to be one of the most negative parameter in terms of noise annoyance or masking threshold increase. On the other hand, spectral composition, temporal morphology or interactive modalities are also identified – although not studied very much yet – to be significative factors able to play a determining role in the efficiency and neutrality of a given added sound with regards to the diversity of environmental backgrounds; these componenents seem to be eligible candidates for assuming integration and acceptability of possible future quiet vehicles' sound signatures.

In that field, the Ircam / Sound Perception and Design team has followed an inductive type approach: going from the *specific* of an applied project with a car manufacturer to the *general* of formalized ideas subject to propose a conceptual framework for investigating the EV's quietness questions. From the experience feedbacks compiled in several domains during the long-term industrial collaboration (integration of concepts, sound synthesis, interactivity, feasibility, etc.), a lot of open questions have emerged. Some of them – especially concerning the relationship between detection and timbre – have been investigated in a preliminary study which points out promising results such as a quantified learning effect in the detection paradigm. The whole questions have been structured with regards to their associated scientific fields (auditory display, man-machine interface, psychoacoustics, sonic interaction design, etc.) and may constitute as many possible research guidelines for this non-negligible and not yet solved issue.

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