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Electric and Autonomous Vehicle: from Sound Quality to Innovative Sound Design

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ABSTRACT

This study follows long-term lines of research and realizations accomplished within the frame of electric vehicle sound design. It currently deals with the most up-to-date issue addressing the near future mobility: Autonomous Drive (AD). It has been implemented in a 2-year collaboration with a french car manufacturer that deployed a high-tech *demo-car* where the sonic dimension was explored in a spatial and a multisensory approach. Specific hardware devices (multi-channel diffusion system) and software protocols (spatialization and vehicle data transmission) made possible the study and realization of numerous and accurate internal/external warning sounds and auditory Human-Machine Interfaces. The autonomous driving condition was especially considered as it corresponds to an unprecedented user experience in terms of human-centered process, where sounds could play a crucial role for informing and, if necessary, reassuring the driver and passengers. This paper presents a thorough analysis of the project: initial requirements and data, multi-disciplinary framework, technical details, sound concepts and realization. It also opens onto reflexive and prospective considerations about the global notion of sound quality that especially look at possible forms of *low-intrusiveness* in sound design, and their related properties.

Keywords: Sound design, Human-Machine Interface, Autonomous vehicle

1. INTRODUCTION

The project upon which the present paper is based, comes within the broader frame of sound design for automotive industry. In fact, the vehicle cockpit is a place – and the driving situation is a moment – where a large number of intentional informations (see Langeveld et al. (1) for the concept of “intentional” sound) is given to the driver – and incidentally, to the passengers – at different levels of significance (2): from very urgent (warning of a sudden dysfunction, for instance the temperature increase in the cooling circuit), to just informative (notification of a standard action, for instance the blinker triggering). These functional informations are mainly transmitted by two sensory modalities: vision (lights and icons on the dashboard) and hearing (sounds playing the role of auditory displays, or what can be alternatively called *sonic Human-Machine Interfaces – HMI*); and, this is without considering the vibro-tactile solutions that strongly tends to emerge …. (3,4). This being, the recent developments of new vehicles types (smart-connected and/or electric-silent vehicles) and new driving configurations (in particular, the different levels of autonomous drive) lead to reinforce the dialogue between *Human* (driver and passengers) and *Machine* (car), and therefore, the need for relevant, efficient, coherent and, a fortiori, pleasant human-machine interfaces.

Within that frame, we recently contributed to an important and long-term industrial project (2016-2017) led by the car manufacturer Renault, that aimed at developing a *demo-car*[3] called Symbioz. This contribution involved our research team in sound perception and sound design (Ircam-STMS / SPD) and a collaboration with a composer/sound designer (Andrea Cera) with whom the team used to work for many years on that global topic (5). The unique specimen of Symbioz is an

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[3] in the automotive world, a *demo-car* – literally called *Integrated Technology Demonstrator - ITD* – is a type of product placed between a *concept-car* (fully experimental, even sometimes unable to move by itself) and a car produced *in mass* (resulting from an industrialized process and commercialized).

electric and autonomous car experimenting and integrating most of the up-to-date technologies available in the automotive industry, and especially the level 4 of autonomous drive assistance (see Sec. 2 for more details). In a user experience (UX) point of view, Symbioz represents a vision of the near future mobility (by around 2030): it is a tentative of fusion between a vehicle and a living space. The care for the passenger's comfort and peace of mind coexists with the experimentation of innovative technologies for controlling the car's behavior, internal atmosphere and feel. In that scope, the whole project has developed a multisense design approach involving research and applications in different design domains such as texture, color, light, sound, and even scent.

With regard to sound, the project offered two main sound design challenges: the design of an external VSP sound (*Vehicle Sound for Pedestrians*), and the design of a collection of sounds for the car's interior (cockpit sounds). The VSP comes in the standard issue addressed by the silence of electric vehicles that should nevertheless signify their presence (6). This part will not presently be presented as it is mainly based on results derived from previous projects assumed by the same research team (7). The present paper will focus on the internal cockpit sounds that really constituted a laboratory for studying the future of *sonic HMI* in the automotive context. We then designed innovative solutions considering two main directions – further detailed in the paper:

• Exhaustiveness. We processed all passengers / cockpit interactions related to the three constitutive and explicit Symbioz's driving modes: Classic, Tonic and Autonomous. But more precisely and interestingly, the availability of the Autonomous driving mode created new design challenges, such as: how to communicate the levels of autonomy, or attention, of the car and its processing unit? How to reassure the passengers that everything is OK when the car is self-driving?

• Spatiality. On the basis of the dedicated sound diffusion device implemented in the car, we developed an original concept of *spatial sonic HMI*. Every sound played in Symbioz's cockpit (blinkers, alarms, info sounds, …) is placed in a virtual acoustic space. In each driving mode, the sounds slightly move around virtual positions, with different degrees of jitter and reverberation. For instance, in Tonic driving, blinker sounds are firmly placed in the direction the car takes whereas in Autonomous driving, these same sounds are oriented much loosely, since no passenger focuses on driving. By moving in space, HMIs become less intrusive/annoying and more natural, as spatial changes translate into subtle timbral shifts (due to phasing and reflections in the cockpit's walls).

Then, as a challenging and original user context, the paper focuses on the Autonomous Drive (AD) sequence and furthermore develops all the ins and outs of the workflow: from the conceptual and multidisciplinary brainstorming of the role of sound in that context (sec. 2.1) to the description of the final designed sounds (sec. 2.4), going through presentation of the technical frame (Sec. 2.2) and the methodological process (Sec. 2.3). Then, in order to open this experience to discussion, we sum-up what we learned from the project (Sec. 3.1), considering it as a potential *project-grounded research* that implements a *research-through-design* approach (8) in sound design and that aims at contributing in *sciences of sound design*, a conceptual framework that we tend to progressively implement (Sec. 3.2). For that, we especially focus on the concept of "*low-intrusiveness*" (Sec. 3.3) that arose from this industrial collaboration and could be a strong and relevant guideline for future sound design contributions in that particular, or any other, applied domain.

2. FOCUS ON AUTONOMOUS DRIVE SEQUENCE

2.1 General Description and Sonic Challenge

As previously mentioned, the Symbioz demo-car gets three driving modes among which the Autonomous Drive (AD) represents an unprecedented user experience, and more broadly a future new life situation. It mainly consists in giving to the car the ability to make decisions concerning the drive without any human supervision or intervention. The level of autonomy implemented in Symbioz is at the standardized level 4 – also called *mind off* level – (9), ranked just after levels 2 and 3 (respectively *hands off* and *eyes off*), and before level 5 (*steering wheel optional*). This particular level 4 theoretically allows the driver to have another activity than driving, such as reading, working, moving a film or even sleeping! The kinds of decisions the car could then be able to take are, for instance, speed adjustment, vehicle overtaking, line change, urgent breaking and all the functional actions such as trigger/validation of the Autonomous Drive or return to a Manual Drive (actually, Classic mode). For that, the vision and the monitoring of the road and its vicinity is assumed to be 360° wide by means of a large number of sensors placed around or inside the car: frontal or angular radars, LIDARs systems (LIght Detection And Ranging), digital cameras, ultrasonic devices, etc. All the data captured by this exhaustive equipment are analysed by central processing units that are embedded in the car and aimed at defining the best course of actions for a safe and pleasant drive.

In that frame, the role of sound seems then naturally relevant, and even crucial. In fact, being Autonomous Drive an *eyes off* situation by default, visual informations are obviously no longer efficient to transmit informations about the vehicle state – and especially if the driver needs to regain control of the vehicle. Moreover, Autonomous Drive inherently involves the fact that driver and passengers must be fully confident about the *brain* capacities of the car in order to delegate their role without any apprehension. This cognitive mechanism is usually called *re-assurance* (10,11): it targets trustworthiness of the artificial intelligence responsible for driving and tends to evacuate all kinds of uncertainty and doubts in user's mind. Among other factors, *re-assurance* can be promoted by several cues of good functioning sent by the central processing system to the passengers, during the autonomous driving sequence. According to what we stated above, these cues must be sonic cues and should be as meaningful as possible to deliver the right information at the right moment, without being too intrusive nor annoying. All these latter issues form the global challenge of sound for electric/autonomous vehicles in general, and for Symbioz in particular.

2.2 Technical Frame

Relatively to the sound component, the Symbioz project rested upon a complex technological framework and apparatus. It is mainly based on a two-fold architecture mutually connected via a direct physical link (USB) and supplied by input parameters coming from the internal car network. The two parts of the system are: *i)* an encoded sound database stored in memory and an audio playback library running on the central system processor unit (Nvidia GPU) ; *ii)* a multichannel spatial decoding software attached to a 16-point hardware diffusion device implemented in the car (adapted from the Phantom technology by Devialet[4]). For any of the 60 *sonic HMI* of the sound collection designed for Symbioz – especially those concerning Autonomous Drive –, the synopsis of the technical protocol was the following: from an information sent by the central system concerning a current vehicle's state (e.g., battery level) or an action currently achieved in the cockpit (e.g., blinker), the corresponding encoded HMI is selected and sent to the multichannel component which decodes its features (level, loop size, etc.) and its spatial properties, then implement and play it on the hardware diffusion device via a proprietary virtual acoustic rendering tool.

The multi-loudspeaker system proposed by Devialet was inspired by the initial idea to make converge the inside of the vehicle with the living space (see above). It offers an original listening experience inside automotive cockpit by means of two dedicated hardware developments. First, miniaturized sound diffusion modules (inspired by the Phantom technology, adapted to low acoustic load volumes) replacing traditional in-door speakers, and located in the dashboard, B-pillars and behind the rear seats. Second, the "Diffusors", which are placed in empty spaces of the cockpit's structure and are connected to the modules in order to create a network of virtual loudspeakers and increase the degree of freedom in terms of spatialisation and immersion. With regard to this very specific sound apparatus and technology, the testing and tuning phases were done on a back-up car (with nearly the same interior volume and configuration than Symbioz) during the major part of the project. Because of the complex and highly multidisciplinary development of the demo-car, we only had at our disposal few workshops on a Symbioz mockup (Figure 1a) and two tuning sessions on the final release of the vehicle for an ultimate tuning phase before the official reveal (Figure 1b).

Figure 1 – (1a, left) Works on the Symbioz mock-up by different teams (software, sound, light, etc.) at Renault's studio; (1b, right) Works on the Symbioz final version in the very late of the project.

[4] https://www.devialet.com/fr-fr/story-symbioz-demo-car/

2.3 Sound Design Process

The development workflow of the 60-item sound collection mainly involved the design and specification of two main sonic dimensions: timbre (spectral content and temporal evolution), and space (localisation, spatial image and dynamics). A third basic dimension was also carefully taken into consideration during the testing and tuning phases: intensity, i.e. sound level at which the *sonic HMIs* should be diffused with regard to their functionality or context of use, and that directly relies on their saliency with regard to the background noise (see also Sec. 3.3).

Conception of timbres was done in the frame of the multisensory design approach mentioned above. It was inspired by the research work made by Superface design agency[5] on the materials used to fit cockpit's structure (doors, top) or elements (seats, dashboard). Moreover, several physical samples available in Superface's material database and involved in this design research (wood, aluminium, bakelite, etc.) served as primary sources of sound that were thoroughly recorded and used hereafter in different transforming/mixing processes to answer some insights of the overall design brief (authenticity, expertise, crafts, collective memory, etc.) and relationships with the other modalities, especially lights and colors.

Conception of spaces was also done in the same multisensory design frame and tried to answer another important part of this same brief that specified on how to "sculpt" the inner space of the cockpit. For that, we used the multichannel Devialet device in order to develop the concept of *spatial sonic Human-Machine Interface*. In fact, each HMI of the collection was placed in the 3D-space of the cockpit by defining its localisation (*azimuth* and *elevation*), its spatial image (*width*) and its dynamics (*jitter*), the latter describing how the spatial features evolves along time. Values and ranges of these parameters – together with the modeling of a virtual room acoustics of the cockpit – were fitted to the main character attached to each driving mode: Classic → neutral/natural, Tonic → focused/damped, and Autonomous → amplified/diffused (Figure 2)

Figure 2 – Depiction of the spatialisation concepts of the three driving modes of Symbioz: natural for Classic (left), focused for Tonic (middle), diffused for Autonomous (right)

This being, this complex sound design process led us to develop ad-hoc tools for prototyping and harmonizing the whole set of sounds. First, an environment for realizing quick prototyping based on basic components (oscillators, broadband noise, filters) was especially built to sketch gross-categories of HMI's spectral contents and temporal morphologies; these sound mock-ups were then refined by applying different sound materials (resulting from the recorded samples mentioned above), by means of additive analysis/synthesis or cross-synthesis standard techniques. Second, a meta-scoring environment that gathered all the sound parameters used to design the HMIs was implemented in order to be able to organize – and harmonize – this large sound production. This kind of holistic approach was quite relevant to manage similarities (invariance) and differences (modulations) in terms of sound description (rhythm, pitch, consonance, noisiness, etc.) either from different groups of HMIs (e.g., Classic, Tonic and Autonomous), or from different HMIs in a same group (namely, Autonomous Drive). This finally helped to reach a certain consistency between or within pre-defined sound categories of the whole collection.

2.4 Sound Design Production

The Symbioz demo-car gets 10 sounds related to Autonomous Drive (AD) mode and its corresponding explicit functionalities: '*AD Available*', '*AD Definitive*', '*Hand Over Notification*', '*Hand Over Required*', '*Minimum Risk Maneuver*', '*Back to Manual driving*', '*Urgent braking*', '*Line change*', '*Trajectory change*', '*Everything OK*'.

[5] https://www.superface.fr/

These sound contains 3 types of message, ranked in crescent order of driver-agency relevance:
1. Multi-sense HMIs. A few HMIs are used to reinforce the sensorial impact of the car, in particular the dynamics of light and scent design, which change according to the selected driving mode. For instance, if AD is selected, the audio HMI is very bright, consonant, with smooth attack and release shapes, and a soft diffusion level suggesting low tension, calm, and focusing on bright, sky-like lights. These HMIs have long durations (5 to 10 sec.), mimicking the slow evolution of lights.
2. Low driver-agency relevance HMIs. Some HMIs simply aims at informing driver/passengers about decisions made by the central processing system. We call them “*brain sounds*”. They are used to reinforce and reassure passengers that the autonomous driving operates without flaws. The ones called *Line change* and *Trajectory change* inform that the car makes a change of direction, before the centrifugal force shift is felt. The one called *Everything OK* is a periodic reminder that everything is working well and under control. For these sounds we used a *low-intrusiveness/annoyance* paradigm (Sec. 3.3). We created short and high pitched sounds (fundamental between 5 and 8 kHz.) which can be diffused at low amplitude in the cockpit and still be clearly perceived, without being aggressive.
3. High driver-agency relevance HMIs. Other HMIs are much more important from the driver–car relationships point of view, as they signify the need for a specific action. In that case, we decided to shape them by using the concept of “earcons” (12): musical signals with specific meanings, that usually imply a learning process. Their fundamentals’ pitch-range are lower (200 to 500 Hz), and their duration are longer (main sections of 1000/1500 ms., followed by a reverb fade out).

For AD switches, we used the bichord [G B] to signify *availability*, and the bichord [Bb D] to signify *locking*: i) with the presence of a *brain sound* and a slow relaxing fade-out to signify that the system is locked in AD mode (the *brain sound* signifies the on-going process to AD mode; the slow fade-out suggests the possibility to keep hands off the steering wheel … and relax) ; ii) without the presence of a *brain sound* and with a faster, more dynamic, fade out to signify that the system is locked back in manual driving mode. We used a dissonant mixture of the 2 former bichords [G Bb B D] to signify that the AD mode needs to be abandoned, to go back to the manual driving mode.

For the *Minimum Risk Maneuver* situation, we used a single note [A], that is different from the previous ones: the car is going to stop, because the AD process has failed and the driver didn't take over. This is a rather serious situation which has two levels of severity. Therefore, we designed two version of this specific HMI, with two different levels of perceived urgency: the first one is a loop of 2500 ms., with a smooth timbre, meant to warn passengers without panic; in contrast, the second one has a pulsation of 500 ms. and a timbre characterised by a high roughness ratio – in other words, a classic alarm sound, announcing the danger of a possible impact.

Figure 3 shows the sonogram of the sound *AD Definitive*. It begins with a fast succession of two *brain sounds*, to remind passengers that the car is in Autonomous Drive mode. The next section signifies the locking onto AD mode, with a smooth fade-in and a slower fade-out, meant to suggest that the pilot can take hands off the steering wheel. Finally, the end of this HMI is a cross-fade with a longer and brighter sound synchronized to the change of the light system's brightness.

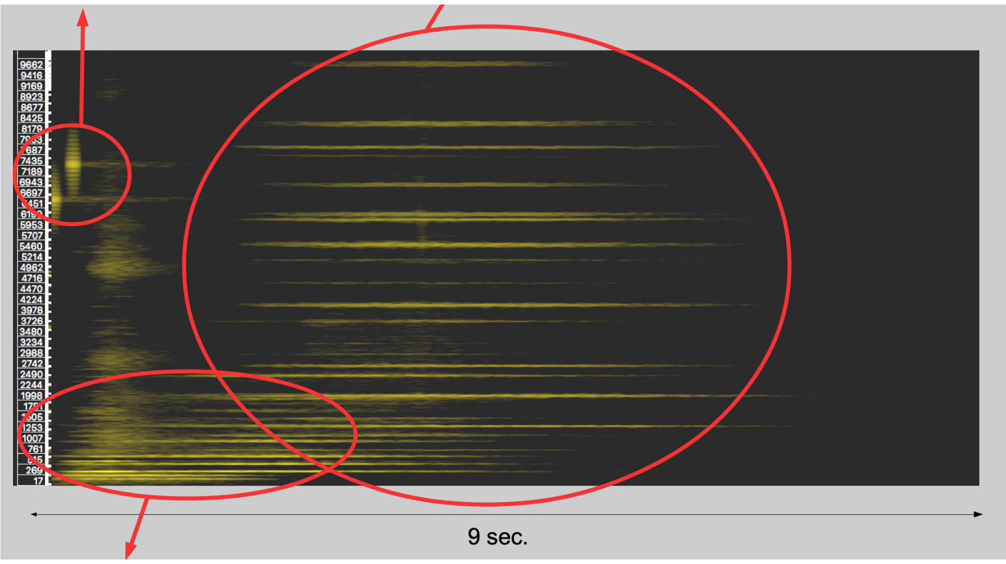

Figure 3 – Sonogram of *AD Definitive* HMI (from left to right red circles): *brain sounds* reminding AD mode setting; sound confirming successful locking in AD mode; multisense sound reinforcing light design.

3. ZOOM OUT OF THE PROJECT

3.1 What We Learned?

The extreme density and complexity of the Symbioz project, added to its multidisciplinary aspect, makes it relevant to include it in a *research-through-design* approach (8), and then consider it as a *project-grounded research* that aims at "producing knowledge instead of only solutions" (13).

Globally, the Symbioz experience brought lessons in three main areas. First, multisensory design that led the sound design process to be inspired of, and composed with, other design dimensions. This involved fruitful collaborative design sessions conducted by designers (the Superface team) that resulted in transforming formalized design brief and insights to integrated design elements either in visual, auditory or olfactory domain. This forced to think about sound no more by itself but rather in interaction with other perceptual or experiential dimensions. Second, the intrinsic inclusion of technology into the sound design process that, at some points, appeared to be more densifying than lightening the integration of sonic components in the whole project. Actually, this densification mainly came from the fact that Symbioz was a high-level technological project and that its priority target, in terms of technology, was naturally the autonomous driving function. This assumption consequently addressed issues about technological independence of the sound design discipline – for how much should sound be dependent from its technical environment? –, but also about technological sobriety that leads, in a way, to reconsider the Bauhaus approach – and especially Mies Van der Rohe's maxim "less is more" – in the light of sound design. Third, the crucial needs of tools for prototyping and composing sounds. Here, the multiplicity of the application (60 *sonic HMIs* in all) led sound designer to develop generic tools to methodically build sound matters and morphologies (*sketcher*) and organize/arrange them in a pitch-rhythm-timbre parametrical space (*meta-score*). This pragmatic paradigm – that appeared to be efficient either for production but also for collaboration – could be related to the contemporary music composer practice when he/she works on the electronic components of his/her piece, gathering sound materials (record, synthesis, etc.) then making the arrangement with other sound sources (instruments, voices, etc.) in a global score.

Moreover, the main lesson that could be learned from the particular context of Autonomous Drive application is that sounds could definitely play a leading role in (future) daily life situations where other sensory modalities are obstructed or already recruited. This assumption has been objectively demonstrated by several previous scientific works in many different domains such as aircraft cockpit (14), control room (15) or surgical operating unit (16). In the automotive frame, among many others, Tardieu *et al.* showed that sonifying the navigation process in a cockpit central unit (processing GPS, listening to music, searching contacts, … in the on-board computer) significantly increase the time spent to look at the road – the driving attention –, and decrease gaze movements from the windscreen to the computer screen (17). In the Symbioz Autonomous Drive configuration, driver/passengers' sight is theoretically used for any other things than looking at the road or at the dashboard. Then – even if it has not yet been objectified as such – it seems that sounds could be of a great help to make driver and passengers better informed of what currently happens, more confident in the technology and finally more safe, for instance, by avoiding wrong interpretations and unexpected actions.

3.2 Contribution to Sciences of Sound Design

The last elements of reflexion (Sec. 3.1) precisely comes into the conceptual frame we recently tried to make emerge and promote about sound design, in a tentative of integration of this field into the broader scope of design research. In fact, by especially transposing Nigel Cross' vision of "science of design" and his formalization of three design research sources (*loci*) – "*people*, *processes* and *products*" – (18,19), we look at laying the foundations of *sciences of sound design* that will respectively investigate the character of the sound designer, the sound design processes, tools or methods and the status of the designed sound, i.e. what sound design finally produces (20). Then, to some degree, we can expect that the present project may help to contribute to this approach and inform it. For instance, the two tools built on purpose (*rapid sketcher* and *meta-score*) or the conceptual thought on *low-intrusiveness* developed at the beginning of the Symbioz sound design process – and partially inspired by interactions with other design fields – bring links for a global knowledge on sound design, here understandably considered as "a discipline of study in its own right" (21) (see precisely Sec. 3.3 below for a development on low-intrusiveness). In the end, and quoting Cross (18), this may give some elements for answering the seminal – and open – question: is there a designerly way of knowing, thinking and acting in sound design?

3.3 Immediate Intrusiveness *vs.* Long-term Annoyance

Indeed, the Symbioz demo-car project has been a fruitful laboratory to explore and refine a series of ideas and guidelines about *low-intrusiveness* and *low-annoyance* sound design. Actually, we started developing these guidelines since years, during our long-haul collaboration with Renault. During many projects, and thanks to reports from testers and clients, we had the opportunity to study how sounds played inside a car cockpit might be immediately perceived as intrusive (at first listening), or could become annoying in the long term (after repeated listenings).

On this basis, and with the support of literature (22, 23), we started to draw few principles about designing sounds with a minimum of intrusiveness and annoyance impact on the listener. These pragmatic hypothesis are as follows: (a) foreground/background: intrusiveness of a sound is related to its background; (b) timbre: a few timbral features are directly linked to intrusiveness; (c) duration: intrusiveness of a sound is linked to its duration; (d) memory: annoyance can be enhanced by the presence of easy-to-remember pitched elements and rhythmic patterns; (e) context: the user context in which sounds are heard plays a role in determining if and how people judge them as annoying.

But, there are three inherent difficulties in considering these guidelines. First, they constitute a system of constraints by themselves, with their ingrained complexity. Second, they might be in direct contrast with standard principles of sound design. For instance, in a complex human-machine interaction (e.g., airplane cockpit) a certain type of sounds, such as important alerts, are processed as *earcons* (12) that needs to be learned and stored in memory; this feature being in contradiction with point (d) above. So, this means that, sometimes, *low-intrusiveness* and *low-annoyance* are features which can't be assigned to particular sounds. The third difficulty is that in a sound design project, solutions to point (a) and (e) are not exclusively in the hands of sound designers. For instance, the quality of the background sound in a car cockpit depends on how much the car manufacturer decides to invest in isolation and sound-proofing. In conclusion, *low-intrusiveness* and *low-annoyance* can be obtained only if all the stakeholders of a project agree on their importance.

This being said, the sounds played in Symbioz's cockpit were tentatively designed by following the guidelines described above. Low driver-agency relevance sounds, destined to be passively heard many times during a trip (e.g., *brain sounds* – see Sec. 2.4), tried to be made as less intrusive and less annoying as possible. Actually, they were produced, mixed and diffused in order to minimize their emergence from the cockpit's background noise, while maintaining a minimal saliency to ensure their audibility. On the other hand, important auditory alarms, destined to be heard in very exceptional cases, were designed to clearly emerge from the background, then paying little attention to point (d).

4. CONCLUSIONS AND PERSPECTIVES

The Symbioz demo-car project has focused on an electric and autonomous vehicle and the ways of implementing unprecedented user experiences in the automotive domain – or broadly the near future of the mobility. One of these experiences is supported by the Autonomous Drive (AD) mode that Symbioz has implemented in the fourth (*mind off*) standardized level. This driving mode allows driver/passengers to do something else than driving, and even looking at road or dashboard, and subsequently allows sound to play an important role in the human-machine communicaiton process. In that frame, *sonic Human-Machine Interfaces (HMI)* were designed, produced and implemented in Symbioz cockpit, that relied on the highly technological software and hardware environment that the demo-car provided, especially considering the embedded multi-channel sound diffusion system which led to define the concept of *spatial sonic HMI*. This complex and multi-disciplinary project also allowed us to develop thoughts (the concept of *low-intrusiveness*) and tools or methods (*rapid sketcher* and *meta-score*) which can contribute at the same time to formalise the sound design process, to increase generic knowledge on this discipline and to draw the conceptual framework of *sciences of sound design* that we progressively tend to promote.

The perspectives of such a project could be plentiful, either in the short, medium or long term. In the short term, the crucial question of evaluation of the designed sounds (especially in the AD mode) naturally raises and could be potentially considered in a more analytical approach using, for instance, a car simulator or a virtual reality protocol to test the relevance of the produced artifacts together with their underlying hypothesis. In the medium term, the question of transposing the current sound design process to an industrialised frame (e.g., a mass production) could be of a great importance, as the present approach still implemented prototypic approaches (according to development workflow, tuning methods, etc.) that would be hardly feasible in an industrial context. In the long term, the question on how this singular experience in the automotive world could impact a general reflexion on the use of sound for interactions between human and machines could be opened and, if need be, transposed to many other research and application fields, among which the medical or spatial ones.

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