Automotive HVAC NVH quality: from design to vehicle integration

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Abstract

Automotive Air Conditioning (A/C) system (Cold and hot loop + HVAC: Heating, Ventilation and Air Conditioning) is the major contributor for thermal comfort of the passengers. For years, Valeo as a supplier of systems and products for automotive industry takes into account the end users "global comfort" including the NVH (Noise Vibration and Harshness). Research activities, based on objective measurements and subjective evaluations, of automotive's HVACs have been conducted in collaboration with universities and technical centers. It was found that the global comfort of the automotive's drivers and passengers is a formula that mixes acoustics, thermal and air flow [1]. Commonly, and depending on the environment, an acoustic signal can be perceived as sound or noise. For the car users, a Natural noise (Sound) appears as information or after an action from the users (ex: air flow noise).These sounds are acceptable thanks to the feed-back of the end-user action and perception of quality. An Annoying noise (Noise) appears without action of the end-user or information (ex: humming noise, pulsation noise of the compressor, A/C flow injection, etc). These noises are not acceptable, can be perceived as a failure and often with bad noise quality [2]. Car makers as well as the suppliers are watchful to the end users complaints concerning the non natural noises.
At VALEO, NVH is taken into account from design to the integration in the vehicle (+ the useful life time of the vehicle). During the design phase, the designers and test engineers apply NVH recommendations [3] to design a HVAC unit that can achieve the car manufacture specification and users comfort. In the production sites, the NVH recommendations are also taken into account for material choice, injection process and assembly process.
The product alone can achieve the NVH specification but an uncontrolled integration in the vehicle could have a negative impact on the noise level and the sound quality. So, a shared work with the car makers is a prerequisite to avoid all NVH risks. This phase should start from the beginning of product's design.

1 Introduction

In the last few years, a significant evolution in automotive industry is accelerating. The electrification (µ-hybrid to the full electric) is the first step in this evolution. In the near future, the second step will be the autonomous cars (partial or complete autonomous cars). In addition, downsizing and worldwide common platforms are still a natural tendency of the automotive industry world.
The impact of this change for the end users must also be taken account by the NVH community. The NVH is today an important part for the end users comfort. Noises that are naturally accepted or needed by the end users today may not be acceptable and can become annoying in the future. The challenge for the NVH community is, first, to identify the natural noises and non-natural noises for the future vehicles. The natural noises should be in line with the technology used and the future users need.
The thermal comfort is an essential criterion in today's vehicles and in future vehicles. The Air Conditioning system is the major contributor for thermal comfort of the cars users. However, the A/C systems noise can emerge as a primary source of annoyance as the future vehicle background noise is lower than today vehicles. VALEO Thermal System as system supplier, designs, manufactures, and supplies HVACs to car manufacturers. For years, the VALEO NVH recommendations are implemented into HVACs system (as well as the other products), from design to the integration in the vehicle (+ the life time of the vehicle). A database of Valeo Standards, gathering all NVH recommendations, has been created and shared with global teams R&D, process and quality. Parts of recommendations are also shared with the car manufacturers to insure good integration in vehicles. In this database, two kinds of noises are considered, natural and non natural noises (annoying or disturbing).
In this paper, after the definition of natural and non natural acoustic signals and brief description of operating of the HVAC system, examples of HVAC natural and non-natural noises will be given. Recommendations to avoid and/or improve each type of noise will be detailed.

2 Definition: Natural and non-natural acoustic signals

Acoustic signals can be classified as natural or non natural. A Natural acoustic signal is a non-disturbing, acceptable, and sometimes needed sound (as a “feedback” mechanism to the listener) - even if the level is high-. Several definitions can be given :

- A signal that appears, increases or changes after an action done by the user,
- A signal that gives a feedback and helps to make a decision,
- A signal indicating a normal operation of the machine,
- A signal indicating robustness,
- A signal related or representative of the environment.

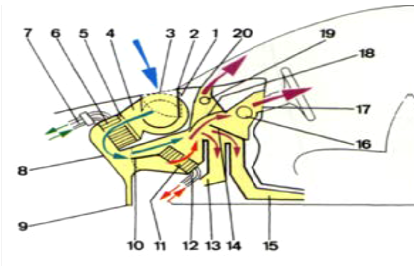
A Non-natural acoustic signal, or "noise" is a disturbing and unacceptable - even if its level is low-. It sometimes can be considered as a failure. Several definitions can be given:

- A signal that appears, increases or changes suddenly without user action,
- A signal that gives non-required information or that could give wrong information,
- A signal not related or not representative of the environment.

The objective for manufacturers is to design their products in order to avoid non-natural acoustic signals: in automotive industry, the comfort is a key buying factor.

3 Heating Ventilation and Air Conditioning

The operating of the HVAC is based on the circulation of cold or hot air (Figure 1). Outside air is picked up at the base of the windshield and then blown inside the vehicle. The air is successively filtered, cooled or heated, mixed, and then distributed into the cabin. Another function is to use the recirculation inlet, which takes the air from inside the cabin to help cool down or heat up the car cabin faster. It is also used in case of detection of polluted air outside the vehicle. To warm up and cool down the air inside the car cabin, two closed loops are today necessary. The cold loop is based on the circulation of a refrigerant. The hot loop is based on the circulation of the engine coolant.



1. Recirculation Air Inlet – 2. Air Inlet Flap – 3. Outside Fresh Air - 4. Blower – 5. Air Filter – 6. Evaporator – 7. Refrigerant A/C Loop – 8. HVAC Structure – 9. Condensate Outlet – 10. Mixing Air Flap– 11. Heater Core –12. Heater Water Loop –13, 15, 16, 17, 19, 20. Air Outlet – 14. Air Distribution Flap – 18. Defogging-demisting Flap.

Figure 1: Automotive Air Conditioning System

The air conditioning system shall satisfy the users comfort in terms of cooling, heating, advanced comfort (individualization, soft diffusion, pre-conditioning), air quality (filtration and odorization) and of acoustics (low overall noise level, good sound quality, no transient noises). On the other hand, the supplier of the air conditioning system must satisfy the car manufacturer needs in terms of packaging, mass, power consumption, and acoustics (overall noise level, sound quality).

As mentioned, thanks to the blower, the air passes through different exchangers and ducts and is blown inside the car cabin and extracted from the vehicle. Thanks to flaps, actuators and steppers, the airflow distribution inside the cabin at needed temperature is ensured. All those components are not known or not visible (under the dash board/Instrument Panel) for the occupants. The only visible thing and used is the HMI (Human Machine Interface: the control panel). The only thing expected by the end user is the comfort. The car makers and the suppliers translate this expectation into specifications of air flow rate, a temperature level and a distribution type. However, both active and passive components in the HVAC can be sources of noise. Each source is identified as electrical, aeroacoustical, or mechanical source. Each type of noise can be classified as natural or unnatural. Valeo has created a database where each noise is identified by detection conditions, the sound frequency band and its characteristic.

4 Examples of HVAC natural and non-natural acoustic signals

4.1 Non-natural: Ticking and U-Tone noises

4.1.1 Description and root causes

As the blower motor is a rotating machine, the magnetic field fluctuation creates vibration according to the number of slots on the rotor. The vibrations are transmitted to the motor housing. Any contact between the motor and plastic parts, such as motor cover, can create a disturbing noise. Due to lower background noise in electrical vehicles, hybrid and electrical cars, the users may be more sensitive to this kind of annoying noises. Example in a hybrid car when the thermal engine is on, this kind of noise can be masked by the engine noise. When the thermal engine is off, the level of background noise cannot cover this kind of noise (see figure 2).

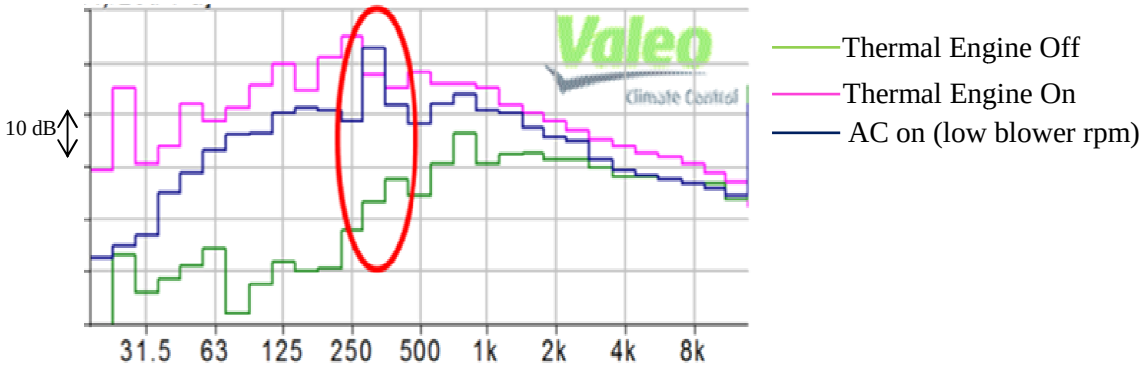


Figure 2: Emergence of motor harmonic noise

4.1.2 Recommendations

Two solutions can be implemented to eliminate this kind of noise. The first one is to define a noise or vibration threshold not to be crossed on 100 % motors end of line test control. The second one is to implement efficient decoupling system between the motor and the motor cover. The second solution is more efficient than the first one because the decoupling system reduces the motor dispersion. In order to reach the car maker specifications and to offer good quality and comfort to the end user, new decoupling system has been developed recently by VALEO. This system is very efficient for thermal power train vehicles and still efficient for hybrid and electric power train vehicles.

4.2 Non-natural: recycling noise

4.2.1 Description and root causes

The recycling air function is used to warm up and cool down the air in the cabin very quickly. This function is also used in case of air pollution (stop the air coming from outside and recycle the air of the cabin). In some HVACs, the recycling air is permanently used to upgrade the thermal performances. To realise this function, the air is picked up from the cabin via an inlet under the dashboard. Due to this opening and because of pressure loss difference in this configuration, the noise inside the cabin can be sometimes totally different compared to fresh air, in terms of spectra, and level. This noise difference will be more disturbing in case of electrical power train vehicles. This will be not acceptable for the end user, especially in case of automatic HVAC - in this case, the end user does not manage the recycling air inlet-.

4.2.2 Recommendations

Use of VALEO recommendations leads to reduce the noise gap between fresh and recycling air. These recommendations are based on two principles: 1- In fresh mode and in recycling mode, air flow and pressure drop of both circuits must be the same. 2 - Direct noise shall not radiate directly through the recycling air inlet. In this way, a VALEO and a car manufacturer patent (**Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**) consists in placing the Fresh and Recycling inlets in the car plenum [2]. In this case, the same pressure losses between the two modes are obtained and the direct emission of the blower in recycling mode is avoided. With this design, the same perception of recycling and fresh air is obtained.

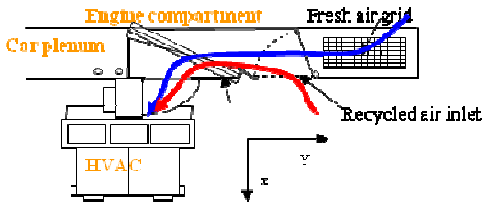


Figure 3: Concept of recycling air inlet

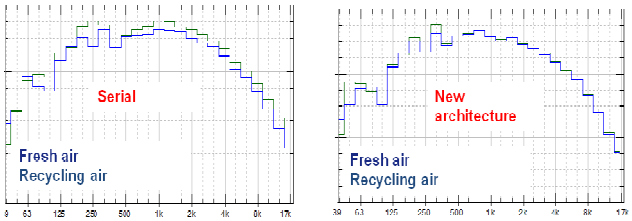


Figure 4: Comparison between recycling and fresh air

4.3 Natural Air Flow noise

4.3.1 Description and root causes

For the thermal needs in vehicle (warm up and cool down) the HVAC unit can produce an air flow rate up to 600 kg/h (~ 290 CFM at standard temperature & pressure), which causes a high noise level. This natural noise : it is needed by the end-user as a feed back for the ventilation system well functioning. Moreover, it must have good noise quality, with "pure" air noise (no cavity modes, whistle, "fallen leaves" noise…), and an acceptable level in high frequencies. This natural noise can be perceived as not acceptable in case of electrified vehicle because of low background noise in electric modes (**Erreur ! Source du renvoi introuvable.**).

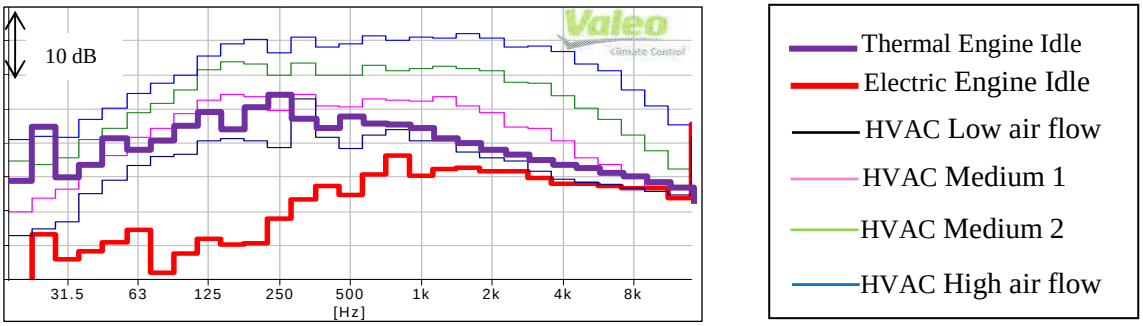


Figure 5: HVAC air flow noise measured hybrid vehicle

The worst case is changing the power train mode from thermal engine mode to electrified mode. In that case, the background noise drops from a level that can cover completely or partially the HVAC noise to a level that cannot cover the HVAC noise. The recommendations done, in case of thermal engine power train, still apply to the electrified vehicles but other recommendations shall be implemented to manage the air flow sound quality.

4.3.2 Recommendations

The noise level of HVAC (overall and 1/3 octave) is linked to the air flow, pressure drop and the efficiency of the blower [4, 5]. Therefore, it illustrates well the impact and great potential of improvement for the acoustic results by decreasing as much as possible the air flow rate and pressure resistance (**Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**). It is possible to predict the air flow noise (overall level and spectra) using a blower pre dimensioning tool developed by Valeo. Two levers can be used to reduce the air flow noise : pressure drop and air flow optimization.

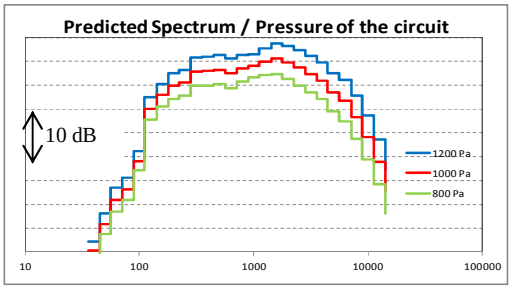


Figure 6: Influence of the circuit pressure

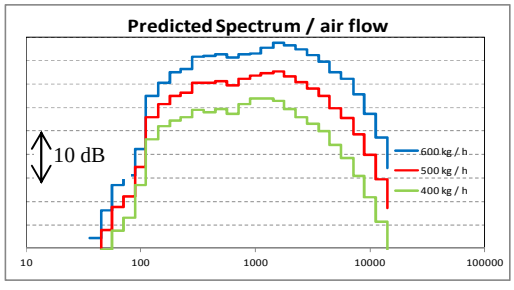


Figure 7: Influence of the air flow

4.3.3 Pressure drop optimization

The total pressure drop of the complete circuit is the sum of vehicle pressure drop and HVAC pressure drop. The HVAC pressure drop is due to air inlet, diffuser, filter, exchangers and distribution circuit. The vehicle pressure drop is due to the water separator, the ducts and the extractor (**Erreur ! Source du renvoi introuvable.**). The blower adapts its rotation speed to overcome this total pressure drop. The higher the pressure is, the higher the blower speed is, and the louder the noise is.
To reduce the air flow noise, the HVAC and vehicle pressures have to be optimized. The pressure drop of each part of the circuit is minimized using car manufacturer and VALEO know how. Several CFD simulations can be necessary to optimize the circuit pressure drop.
The required blower pressure head is reduced; it is also the case of the blower rotation speed and power consumption. In some cases, the dimensions of the blower can be changed to be altered to the new operating point. In some cases there is a physical limit for pressure optimisation. In this case the specification or the packaging has to be reviewed.

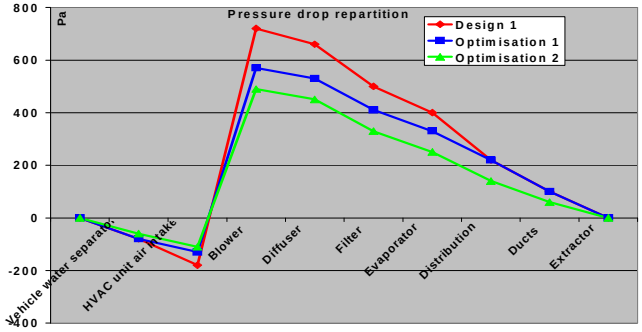


Figure 8: Example of pressure drop optimization

4.3.4 Air flow optimization

There are two approaches to reduce the air flow. The first one is based on new management of the end user thermal comfort. New air flow distribution result in air flow reduction while the comfort is the same. The thermal validation of this approach shows very interesting results. To implement this approach in serial production, collaboration between VALEO and the car makers is mandatory.
The second approach consists in establishing a strategy for end user global comfort. A model mixing thermal air flow and acoustic preference shall be found. Collaboration between VALEO and the academic world [1] was organised, in order to evaluate the end user comfort needs. This study of the psycho-acoustic perception of several HVAC systems provides a classification of several configurations ranked from acceptable to the most disturbing. Correlation between subjective and objective measurements provides a preference model obtained from 2 complementary methods (preference and dissimilarity). Two parameters have been identified in this model: Loudness and Speech Interference Level. These parameters have different influences depending on the frequency. By modifying the acoustic level in a precise frequency band, it is possible to improve the acoustic perception of the end user without changing the overall noise level.
A mixture between the acoustic preference model, thermal needs and air flow rate allows finding a new method of A/C system control to offer a global comfort to the end user. The example in **Erreur ! Source du renvoi introuvable.** shows a new temperature control strategy for cabin cool down, a better comfort curve compared to current production cool down: a slight thermal comfort and air flow performance decrease can result in a drastic noise reduction. The end user prefers the new strategy because the noise level is lower than the production strategy even if the time duration of the cool down is longer.

Objective: cool down the air inside the vehicle from 70 °C to 20 °C	**Strategy 1**	**Optimised strategy**
Time duration to achieve 20°C	30 minutes	35 minutes
Air flow rate	500 kg/h	400 kg/h
Overall noise level	65 dBA	60 dBA
End user head temperature	T=Fct (Time)	T=Fct (Time)+1°C

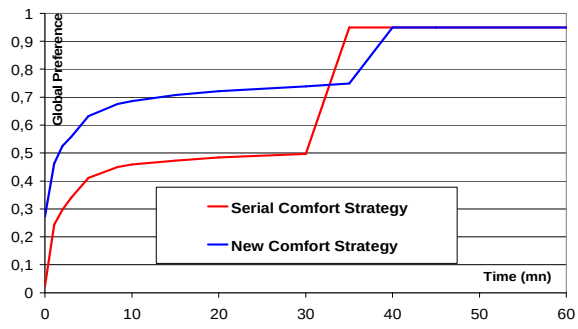


Figure 8: New Cool Down new strategy to offer global comfort

5 Set-up end-of-line control to ensure NVH quality of our products

To develop a robust design to get a mastered natural noise is not the only one approach for VALEO. Acoustic "signature" must be the same for 100% of the HVACs and all of them are controlled to ensure that no abnormal noise resulting from component or assembling failure occurred. Each HVAC system is automatically controlled in acoustic (one or more microphones) and vibration (laser vibrometers) in acoustic box at the end of the assembly line in specific operating modes. These End Of Line Tester systems have proved their efficiency for vibration and aero-acoustic controlled criteria on HVAC systems and for continuous assembly process improvement for many years.

5.1 Description

The EOLT consists of noise and vibration detection system using an industry standard microphone and a high end laser vibrometer inside an acoustically sealed box. A VALEO standardize NVH data acquisition and post-processing system is used to compare each product sound and vibration signature versus predefined limit samples. This EOLT system is not only effective in sorting "bad" part, but it is also more robust and repeatable as compared to human subjective control. As an additional benefit, the system can be "trained" to detect new noises for future issue.

5.2 EOLT Construction and Components

Acoustically sealed box is required to meet the standard low sound level and the vibration isolation method. These requirements are to ensure low level noises (e.g. brush tick and motor commutation tone) are effectively detected and not affected by normal production facility induced noises and floor transmitted vibration (e.g. plastic molding machine). Standard also recommend optimum location for this EOLT system. Microphones are industry standard acoustic transducers with a good S/N ratio, SPL range, and sensitivity. Laser vibrometer is a high end non-contact vibration transducer specially made for production line.

5.3 Measurement Condition and acceptance criteria

Before EOLT is designed into the production process line, three critical steps have to be completed, (1) definition of "Good" and "Bad" parts (ideally is per vehicle evaluation with car maker or an HVAC level evaluation if vehicle is not available), (2) HVAC settings (e.g. blower speed and mode) that induce unwanted noises to check, and (3) optimum location of sound and vibration detection for detection (e.g. strong S/N signal, able to differentiate "Good" versus "Bad") and production friendly in terms of other instruments (e.g. door detection, fixture, etc) inside the box. These steps are done in a laboratory environment. VALEO Standard exists to define acceptance limit. Collecting normal production sound & vibration signatures to define Upper and Lower "Normal" production population.

6 Conclusions

The noises of products intended for the general public are sometimes the first causes of the users' complaints. Therefore, the NVH communities should set-up recommendations to avoid any disturbing noises for the users. At VALEO, the NVH' recommendations are taking into account during the design, the production and integration in the vehicles. At VALEO, The HVAC is designed to achieve the carmakers specifications and end users global comfort including the NVH. To insure the NVH quality and to reduce NVH's dispersion, VALEO has set-up End of Line Testers in production lines. Finally The integration of the HVACs in the vehicle require a close collaboration between the carmakers and suppliers.

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