PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

HVAC noise in car cabin: a preliminary comparison between ICEVs and HEVs

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ABSTRACT

Noise in car cabins is a key aspect of the drivers/passengers' comfort experience. It is produced by the aerodynamic interactions of the vehicle and the rolling, by the engine and all the auxiliary systems installed in the engine compartment. Although cars manufacturers focused their efforts to reduce the noise transmission inside the cabin, for Internal Combustion Engine vehicles (ICEVs) the mainly noise source is still the engine noise. Nevertheless, with the advent of hybrid/full electric vehicles (HEVs) in the automotive industry, the engine noise has been reduced dramatically, especially at low rpm, leaving emerging the noise of auxiliary sources. One of them is the air conditioning noise.

Although doesn't exist a consolidated model to describe HVAC noise perception inside the vehicles, the paper intends to explore the expected changes of the drivers/passengers' auditory perception from ICEVs to HEVs. The acoustic and psychoacoustic metrics of different binaural recordings, carried out inside ICEVs and HEVs, are showed and compared.

Keywords: HVAC, Hybrid Electric Vehicle, Noise.

1. INTRODUCTION

With the transition from the Internal Combustion Engines Vehicles (ICEVs) to Electric or Hybrid Electric Vehicles (EVs/HEVs) the background noise inside car cabins is changing dramatically. It is no longer dominated by the engine, rather, by the secondary noise sources which emerge when the internal combustion engine is replaced with the electrical one. Among all the electro-mechanical components installed in the engine compartment, the heating, ventilation and air conditioning (HVAC) system is one of the most critical from the acoustic point of view, especially when cars are moving at low speed or idling at low engine rpm. Due to this transition between ICEVs to EVs/HEVs, in the next years it is expected that several comfort indexes and sound quality paradigms defined to describe the car cabin noise of internal combustion, will change. Consequently, new measurements and experimental studies need to be carried out on this new generation of vehicles, and new sound quality/comfort predictive models should be developed, to understand the consequences of the technical changes on the noise perception.

HVAC noise has been investigated since some decades, within working environments, such as the offices, to define noise indices (1,2) and to measure its effects on cognitive abilities (3). More recently it became a key element for passenger's comfort in train compartments and inside automobiles, leading to the development of several studies on HVAC sound quality (4,5). In the automotive sector, researches have been focused to represent the perceptual space of the air-conditioning sounds by means of listening tests and subjective questionnaires based on Likert scales, and semantic differential scales, to be administered to a jury (6-10). Only recently the sound quality studies on HVACs have been extended to the HEVs (11), as with the CEVAS project which revealed a 3-dimensional perceptual space, associated mainly to the unpleasantness, sharpness and fluctuation.

This paper describes the first results of a Collaborative Research Project on HVAC sound quality inside cars cabins, between the Department of Architecture and Industrial Design of the Università degli Studi della Campania "Luigi Vanvitelli" and the Department of Communication Design Science,

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Faculty of Design, Kyushu University. In this first phase of the project, some binaural recordings have been carried out, in Italy and in Japan, to characterize the HVAC noise inside ICEVs and HEVs' cabins, in different functioning conditions. Acoustic and psychoacoustic metrics have been analyzed and then used to calculate some sound quality indexes that describe the drivers/passengers' perception inside the cars.

2. MEASUREMENTS SETUP

Recordings have concerned 2 groups of vehicles, ICEVs and HEVs. Each of them was of 4 units. In Italy were measured 3 ICEVs and 1 HEV, while in Japan 3 HEVs and 1 ICEV. Vehicles' brands have been omitted in the paper and the vehicles have been labelled as reported in Table 1. HVAC noise has been measured at the left position inside each vehicle: the driver position in Italy, the passenger position in Japan. During the measurement, the tested vehicles were on a private road inside the university campus. The background sound equivalent level inside the vehicles was less than 35 dB(A).

Measurements have been carried out by: 1) a 4-channel-measuring system, SQobold and a binaural headset BHS II, Head Acoustics, positioned on a Mk1 Cortex manikin (in Italy); and 2) a 2-channel head and torso simulator (HATS) Type 4100, Brüel&Kjær, (in Japan). The position of the right microphone of the HATS/ BHS II was at about 80 cm from the closest central outlet, and at about 65 cm above the seat. During the measurements all the windows and doors were kept closed while all the air outlets valves were fully opened and slightly oriented to the floor to prevent noise induced by air flow at the microphones (12). Recordings have been made compatible by a comparative measurement at the Kyushu University (see Fig. 1) and by the development of an equalizer filters.

Table 1 – Recording labelling

Vehicles category	Italy	Japan
ICEVs	ICEVA, ICEVB, ICEVC	ICEVD
HEVs	HEVD	HEVA. HEVB, HEVC

Figure 1 – Comparative measurements

Each recording lasted 30 s and was carried out at different Functioning Modalities (FMs) and Air Flow Rates (AFRs).

- FM01: represent the background noise inside the cabin, when the engine is ON.
- OV (Only Ventilation): represents a typical ICEV setup, where the drivers/passengers can use the fan to ventilate the cabin, keeping the engine and the air conditioning system OFF.
- VE (Ventilation and Engine): it is the same of OV, but with the engine ON. In case of HEVs the conditions are identical.
- AC/EAC (Air Conditioning and Electric driven Air Conditioning): represent two configurations with the fan and the air conditioning system ON. The differences are: AC) Air Conditioning

system is driven by the ICE; EAC) Air Conditioning system is driven in Electric modality.

Except for FM01, for all the previous functioning modalities the air outlet was set in modality Frontal, with the Air Flow Rate at 4 different levels:

- AFR1: airflow rate 25%;
- AFR2: airflow rate 50%;
- AFR3: airflow rate 75%;
- AFR4: airflow rate 100%.

A total of 88 binaural recordings: 52 for ICEVs (4 vehicles x (3 FMs x 4 AFRs + 1 FM01)) + 36 for HEVs (4 vehicles x (2 FMs x 4 AFRs + 1 FM01)) have been carried out.

Figure 2 – Binaural recordings: Up) HEVs; Down) ICEVs

3. SOUND QUALITY MODELS

Several indexes have been proposed to describe and assess the annoyance and the perceived sound quality of cars, trains or other electromechanical machineries. Among them one the most known is the Psychoacoustic Annoyance model (PA) (13) that combines psychoacoustic descriptors to derive the annoyance rating of people for synthetic and technical sounds (car noise, air conditioner noise, circular saws, drills, etc.). Similarly, other models aim to predict the subjective annoyance to office air conditioners (14) or to washing machines (15). Regarding the transportations means, predictive models have been proposed: to estimate: the subjective responses to HVAC noise (12); the acoustic comfort inside car cabins (16,17) and trains compartments (18); the characteristics that trigger a ‘‘pleasant’’ response from listeners to HVAC noise in automobiles (19).

Some of the previous indexes: Psychoacoustic Annoyance (PA); Subjective ratings (ann, rou, sha); Discomfort (DC), Acoustic Comfort Index (ACI) and Pleasantness, have been used to calculate how they change through different typologies of vehicles and working conditions.

3.1 Psychoacoustic Annoyance (PA)

According to this index (13), the psychoacoustic elements of annoying sounds depend by the loudness, the tone colour and the temporal structure of sounds. PA is calculated by measuring 4 psychoacoustic metrics: loudness, N [sone]; sharpness, S [acum]; fluctuation strength, F [vacil] and roughness, R [asper], with the formula reported below:

$$PA = N_5 \cdot \left(1 + \sqrt{{w_s}^2 + {w_{FR}}^2}\right) \tag{1}$$

Where:

$w_S = 0.25 \cdot (S - 1{,}75) \cdot \log(N_5 + 10)$ for $S > 1{,}75$

$w_{FR} = 2.18 \cdot {N_5}^{-0.4} (0{,}4 \cdot F + 0{,}6 \cdot R)$

3.2 Subjective ratings: ann, rou, sha

These models (12) have proposed the prediction of the subjective response to HVAC sounds using the semantic differential technique. Three equations related to subjective responses have been selected among those obtained as multiple linear regression of several adjective pairs. Subjective responses have been used for not-annoying/annoying, smooth/rough and dull/sharp scales showed below:

$$ann = -2{,}5 + 0{,}24 \cdot N \tag{2}$$

$$rou = -5{,}0 + 0{,}23 \cdot R \tag{3}$$

$$sha = -3{,}8 + 3{,}1 \cdot R \tag{4}$$

3.3 Discomfort

Despite these models (16) are not related to the HVAC noise but to the interior vehicle noise, it is possible to derive them, for different road surfaces, from the loudness, sharpness, roughness, and articulation index. In this paper, only the discomfort index for asphalt was considered.

$$DC_{Asphalt} = 6{,}111 \cdot N + 99{,}572 \cdot S - 107{,}058 \tag{5}$$

3.4 Acoustic Comfort Index, ACI

Like the previous models, also the Acoustic Comfort Index (17), doesn't describes the HVAC sound quality, but only the comfort inside motor cars in different conditions. ACI uses, subjective and objective measurement to estimate the expected comfort in different functioning conditions. In this paper, only the *idle* condition has been used.

$$ACI_{Idle} = -3{,}54 \cdot R + 20{,}07 \cdot F + 0{,}022 \cdot L_A + 22{,}27 \tag{6}$$

3.5 Pleasant

This model (19) uses the results obtained from objective and subjective sound quality (SQ) evaluations of HVAC noise to generate a multiple regression model, that is used with the Semantic Differential Method to determine what characteristics trigger a ''pleasant'' response from listeners.

$$Pl = 9{,}74 + 0{,}399 \cdot N - 4{,}38 \cdot S - 6{,}43 \cdot R - 0{,}151 \cdot (N \cdot S) - 0{,}0611 \cdot (N \cdot R) - 4{,}00 \cdot (S \cdot R) \tag{7}$$

4. ANALYSES AND RESULTS

Representative chunks of 5 seconds have been extracted from each recording and then analyzed by the software Artemis (Head Acoustics). For each of them, the average values of several acoustic/psychoacoustic metrics (L, L_A, N, S, R, F, AI) and some statistical value (N_5) were calculated for each group of vehicles, ICEVs and HEVs.

Due to reflections over the left window, the results showed that the A-weighted sound pressure levels at the left microphone were always higher than the right one, and that they increase as the AFR increases. This is more evident among the HEVs due to the low background noise. The increase from AFRi to AFRi+1 is in average of about +8 dB (Fig. 3 left).

Loudness of HEVs had values lower than ICEVs, in all the functioning modalities, except at the Air Flow Rates 3 and 4 in Only Ventilation modality (Fig. 3 right).

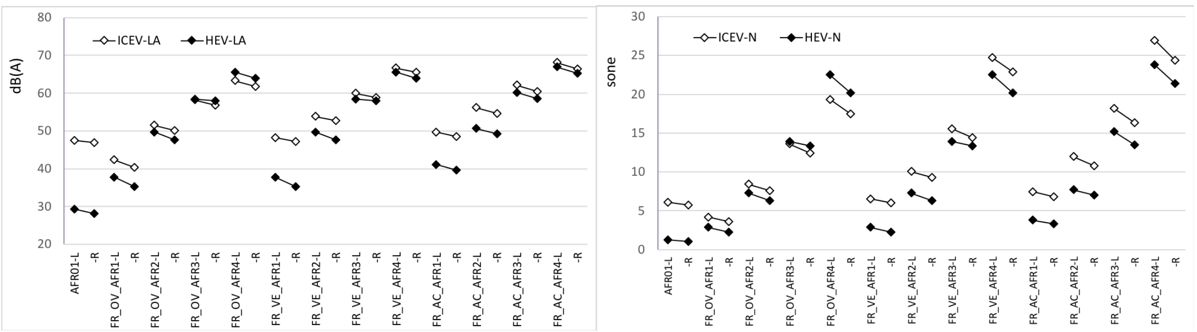

Fig. 3 – Average values of the A-weighted Sound Pressure Level (left) and Loudness (right)

While slight differences were noticed among the measures of the sharpness and roughness of

ICEVs and HEVs, the Fluctuation Strength of ICEVs resulted considerably higher than HEVs, especially, when the internal combustion engine was on and at low air flow rates (AFR1 and AFR2) (Fig. 4 left). At these air flow rates AI was about the 100% and is reduced to 80% at AFR3 and 60% at AFR4. Lower percentage were obtained for ICEVs (Fig. 4 right).

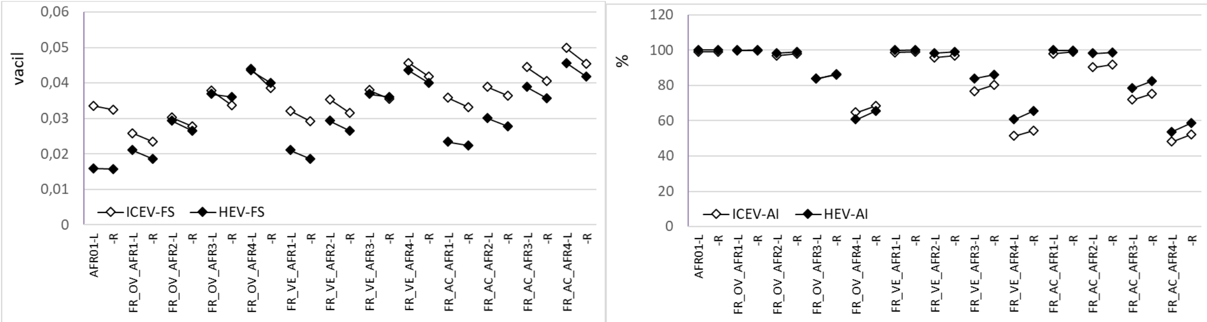

Fig. 4 – Average values of the Fluctuation Strength (left) and Articulation Index (right)

The previous data were combined and used to calculate the above described psychoacoustic indexes. PA and Subjective Ann values of HEVs were higher than ICEVs, only for OV at air flow rates 3 and 4 (Figg. 5). Rou and Sha didn't show significant changes.

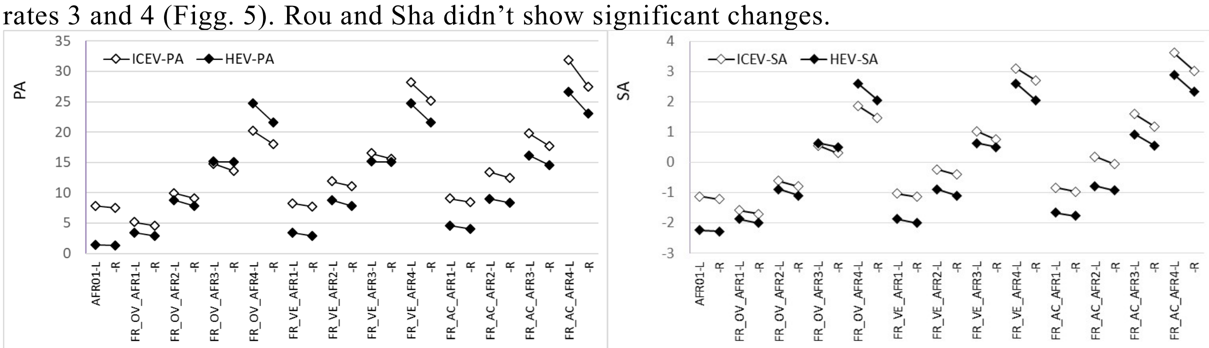

Fig. 5 – Average values of the Psychoacoustic Annoyance (left) and Subjective Not Annoying/Annoying (right).

Considering the Discomfort/Comfort indexes, $DC_{asphalt}$ showed to be in line with the above results while ACI_{idle} appeared to be in contrast with the other indexes for the functional modality AC/EAC. Also, the results of the Pleasant were not sufficiently clear.

5. CONCLUSIONS

The measurement and analyses described above represent the preliminary activities of the Collaborative Research Project on the "HVAC sound quality inside cars cabins". These activities have allowed to describe, preliminary, some differences existing between ICEVs and HEVs in several functional modalities and at different air flow rates.

The most important results emerged from the HEVs and ICEVs measurements showed the greatest differences can be obtained at low air flow rates (AFR1 and AFR2). In these conditions the low noise of the ventilation system and presence the internal combustion engine in idle, makes the Annoyance (see PA and SA) or the Discomfort ($DC_{asphalt}$) of HVAC inside the HEVs considerably lower than ICEVs. The differences between the two engines decrease as the air flow rates increase. In Only Ventilation condition HEVs have the Annoyance (PA, SA) equal or higher (at AFR4). Less clear were the results obtained for the other indexes.

These preliminary analyses suggest to carry out more measurements, including subjective evaluation, and analyses to describe and understand the effects of the combination of different acoustics characteristics on noise perception. This will be developed in the next step of the project.

ACKNOWLEDGEMENTS

Authors want to thank all the colleagues and friends who helped them to carry out the activities of the Collaborative Project "HVAC sound quality inside cars cabins" and who offered their time and

vehicles for the measurements.

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