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THE NVH PACKAGE OF ELECTRIFIED PASSENGER VEHICLES: FUTURE CHALLENGES AND TRENDS

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Electrified powertrains have nowadays become an important development direction for passenger vehicles. In addition to pure battery electric vehicles, a remarkable number of hybrid powertrain models have entered the automotive market in recent years, with many more planned in the future by vehicle manufacturers. This outstanding market change comes together naturally with new concerns in the development of vehicle NVH packages in comparison to conventional internal combustion engine powertrains. This paper presents some direct comparisons of the noise filtering performance measured in a semi-anechoic room and the acoustic performance in operational conditions of different passenger vehicles having electrified and conventional powertrains. On the basis of these results, after considering the current market forecasts and other main trends such as body weight reduction and vehicle architecture changes, it is attempted to foresee the evolution of electrified passenger vehicle NVH packages.
Keywords: Automotive, Vehicle, Car, Electric, NVH

1. Introduction

Powertrain electrification is one of the main technology drivers in the automotive industry today. Pushed by the increasingly severe legislation for the reduction of fuel consumption and greenhouse gas emissions, car makers have been constantly developing and introducing on the market many different electrified vehicle models. Powertrain electrification comes in a wide range of versions, from hybrid vehicles, in both variants plug-in (PHEV) and non-plug-in (HEV), where an electric drive supplements the standard internal combustion engine (ICE), to purely battery electric vehicles (BEV), and finally to fuel cell electric vehicles (FCEV) [1].

Due to their completely different nature, these powertrains are typically expected to introduce some differences in the vehicle NVH (Noise, Vibration & Harshness) behaviour. It is interesting to investigate this field deeper in order to evaluate and understand the possible analogies and discrepancies of the different powertrain types in terms of global vehicle NVH.

2. Aspects and trends affecting electrified vehicle NVH

It is well known that electrified cars have already taken a small slice of the market and their sales have been continuously growing [2][3]. Although there is still a rather spread variety of predictions about the exact development of their market share, the current forecasts mostly agree that electrified powertrains are going to take over a remarkable part of the automotive market at one given point in time [4][5][6]. Thus, it becomes of great importance for NVH part makers to understand how the NVH package will be following this outstanding market change.

There are several variables involved in this process. Firstly, body weight reduction has been a constant effort in the automotive industry in the last decades, in order to contain fuel consumption and the corresponding exhaust emissions.

The importance of this aspect is expected to decrease with electrified powertrains [7][8], however, no matter the powertrain type, body weight reduction generally affects the car handling and crash behaviour in a positive way, while it is not beneficial for NVH (for both structure-borne and air-borne noise). Lightweight alternative materials to steel for body construction, like aluminium (e.g. Tesla) or carbon fiber-reinforced composites (e.g. BMW), are already on the market and, although body weight reduction in general still remains a high priority for car makers today, it is yet to be fully understood whether it will remain a strong need in the long term.

At the same time, a constant cost decrease and technology evolution are foreseen in the near future for batteries, leading to a power density increase against current solutions [1][9][10]. This will make it possible to either decrease the battery weight for the same drive range or to increase the electric mode drive range with the same weight. The current direction taken by car makers seems the pursuit of higher drive ranges, even in exchange for battery size and cost increases (e.g. Tesla [11], Nissan [12], BMW [13]). If this trend continues, the remarkable mass and stiffness contribution of batteries will continue to play an important role in electrified vehicles NVH for long time.

Moreover, electrified vehicles still have to face many of the same important NVH issues that conventional ICE vehicles have faced until today. Tyre and aerodynamic noise is equally present for any kind of powertrain, and ICE noise still plays an important role in the NVH behaviour of hybrid cars. Ancillary systems driven by the engine in an ICE car (e.g. air conditioning compressor, vacuum pump for brake booster), need to be fully electrically driven in a BEV, which also has peculiar additional running components (e.g. battery and electrical motor cooling systems). In addition, also electric motors produce noise, which, although generally lower than that of conventional engines, can be characterized by possible marked tonal components negatively affecting the overall interior sound quality in some frequency range [14].

Vehicle architecture changes are another important factor to be taken into account. In fact, the same body cannot usually be used for an ICE and an electrified powertrain at the same time. For this reason, electrified vehicles have either a purpose-built body or an adapted body derived from a previously existing ICE car. Car makers choose one of these two alternatives, depending on the possible existence of an ICE model and on the battery location. An analysis of the existing electrified car models brings to the conclusion that the battery location strongly depends on its size, which in turn depends on the degree of powertrain electrification (Fig. 1).

BEVs run fully on electric power and have the largest battery packs, which typically need to be mounted in the underbody area. On the contrary, hybrid vehicles have smaller battery packs, which can mostly be lodged in the interior of the car. Plug-in hybrids (PHEV) have a higher share of underbody-mounted batteries than non-plug-in hybrids (HEV) due to generally larger battery packs.

In any case, batteries are very heavy and stiff elements, so they are expected to introduce some non-negligible differences in the vehicle NVH behaviour, especially in the case of large battery packs mounted in the underbody area.

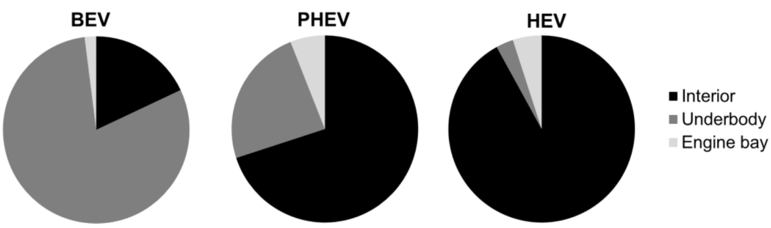

Fig. 1: Battery location market share for different types of electrified vehicles

By looking at the currently available models on the market, it seems that in general car makers try to avoid the risks and costs related to the development of a brand new vehicle body, and prefer to adapt an existing body whenever possible (Fig. 2). This becomes increasingly feasible as the battery gets smaller. As a consequence, about 90% of the existing HEVs have adapted bodies against 75% for PHEVs and slightly more than 50% for BEVs. As much as car makers try to carry over an existing ICE body for their electrified models to the maximum possible extent, they tend naturally to do the same with the associated components, including a large part of the body-mounted NVH package (e.g. inner dash insulator, floor carpet, wheelhouse liners). It also sounds reasonable to expect that car makers will increasingly develop their conventional powertrain vehicles bearing in mind electrified powertrains already from the start to avoid possible cumbersome body adaptations and additional development at a later stage. This is an important consideration because a slow market transition from conventional ICE to purely electric mobility is foreseen, with hybrid vehicles taking the largest share of electrified vehicles sales at least for the next ten years [6][15].

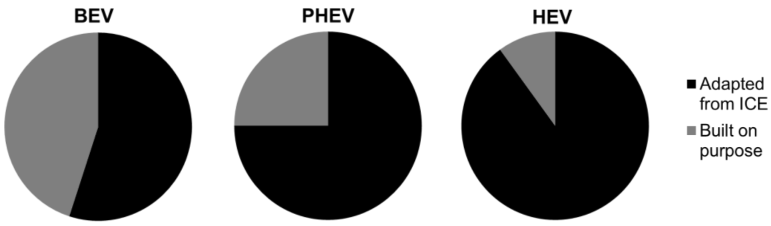

Fig. 2: Body type market share for different types of electrified vehicles

3. Vehicle NVH testing

In order to complement market trend considerations and broaden our current understanding by assessing and quantifying the possible differences and analogies between standard ICE and electrified vehicle NVH characteristics, some experimental tests are carried out on different passenger car models mounting conventional and electrified powertrains. In this paper, the investigation is limited to interior passenger compartment noise.

Two different kinds of test results are analysed [16]. The first test consists in the standard direct measurement of the sound pressure level (SPL) in the passenger compartment with the vehicle in operational conditions during wide open throttle (WOT) acceleration, and at the constant speeds 50, 80, and 120 km/h, each representative respectively of urban, extra-city road, and motorway driving conditions.

The second test quantifies the noise filtering performance of the car interior for both structure-borne and air-borne noise by means of reciprocal transfer functions [17][18]. The vehicle stands on the floor of a semi-anechoic chamber, an omnidirectional acoustic volume acceleration source is placed at the driver’s head, and the interior cavity is excited by a white noise signal.

For air-borne noise filtering performance characterization, the output noise is recorded at different microphone positions, depending on the noise path to be characterized. For powertrain noise, over thirty microphones are positioned all around the powertrain. The transfer function of each microphone is calculated as the ratio between the output and input signals, and the results of all microphones are energetically averaged into a single air-borne transfer function (ATF) curve. For tyre noise, the same procedure is followed with two microphones at each tyre tread, respectively just before and after the tyre contact area with the floor, for a total of eight microphones.

For structure-borne noise filtering performance characterization, the output vibration respectively at the powertrain and suspension mounting points on the body side is measured by means of tri-axial accelerometers. The transfer function for each accelerometer is calculated as the ratio between the output and input signals, and the results of all accelerometers are averaged into a single structure-borne transfer function (NTF) curve respectively for powertrain and suspensions.

For both air-borne and structure-borne transfer functions, lower values correspond to higher (i.e. better) vehicle noise filtering performance.

Fig. 3 shows the SPL versus speed at the front passenger position measured on road during wide open throttle acceleration. The typical dominating noise source here is the engine. Each displayed chart corresponds to a comparison of ICE and electrified vehicles in the same segment, with increasing segment from left to right.

In the left chart of Fig. 3 the SPL at the front passenger position of an A-segment car (small city car), respectively powered by a small gasoline engine (A-ICE) and a pure electric powetrain (A-BEV), are shown. The electric car has an adapted body from the ICE car, the same interior NVH package, and more extended absorption treatment in the engine bay. Both WOT acceleration curves in 2nd and 3rd gear are shown, while for the ICE cars in the other segments it has been possible to do only WOT acceleration test in 2nd gear. The middle chart refers to a C-segment hatchback (compact car) carrying three different powertrain versions: conventional gasoline engine version (C-ICE), plug-in hybrid version (C-PHEV) with the same engine as the ICE version coupled to an electric powertrain, and pure battery electric version (C-BEV). The electrified cars have an adapted body from the ICE car with the same interior and engine bay NVH package. The chart on the right refers to three different F-segment cars (luxury sedan) each belonging to a different vehicle manufacturer and having a different body and engine. One of the cars carries a purely electric powertrain (F-BEV) on an aluminium body with a full e-motor encapsulation, while the other two cars (F-ICE1 and F-ICE2) feature a conventional diesel engine, steel body (respectively 23% and 30% heavier than the F-BEV), heavier interior NVH treatment, and larger absorption treatment in the engine bay.

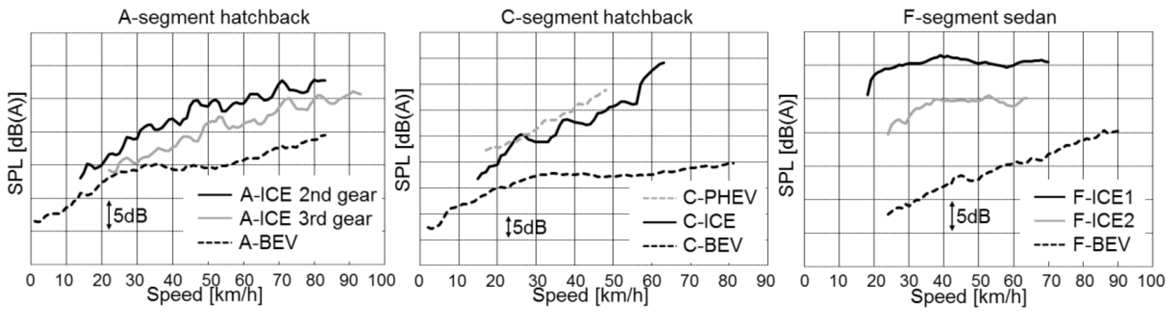

Fig. 3: WOT acceleration sound pressure level at front passenger position as a function of speed

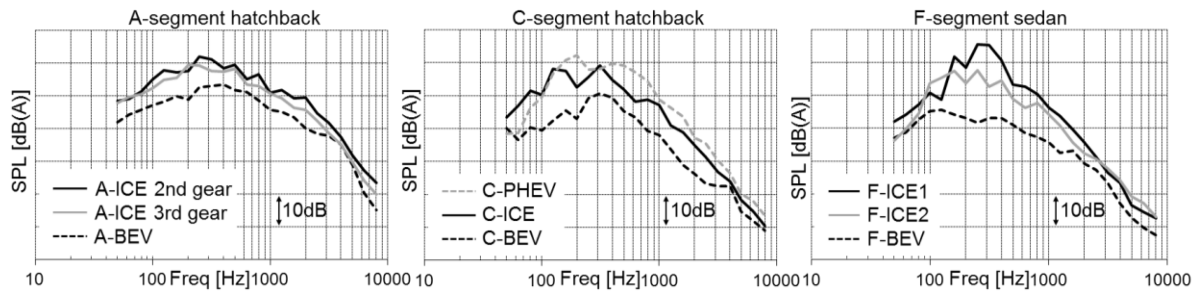

Fig. 4: WOT acceleration frequency spectra at front passenger position

The experimental results confirm that battery electric cars have an advantage on other powertrain types when engine noise is dominant, no matter the body type. The C-segment hybrid car performs in the same range of the conventional C-segment ICE car, which looks physically reasonable since the hybrid has the same gasoline engine with higher power than the conventional ICE version. Particularly severe, although quite expected, is the comparison between purely electric and conventional diesel cars. However, the corresponding frequency spectra (Fig. 4) show that BEV and ICE models have rather similar noise content in high frequency, which needs typically to be masked or absorbed by some acoustic treatment in the engine bay or on the dash.

Fig. 5 shows the interior SPL at the front passenger position at different constant speeds for the same cars investigated previously. The results comparison in this case looks much different than in acceleration conditions: the noise levels of the different cars in the same segment stay close to each other and there seems to be no clear benefit coming from powertrain electrification.

In general, as frequency, speed, and segment increase, the overall noise performance of battery electric vehicles gets increasingly closer to that of the ICE models, and finally becomes worse (luxury segment at high frequency).

The remarkable high frequency content of BEV noise, together with the clear NVH performance worsening as a result of the increasing speed, suggests some high excitation coming from tyres and aerodynamic noise sources, possibly coupled with some weakness in the vehicle noise filtering performance in that frequency range.

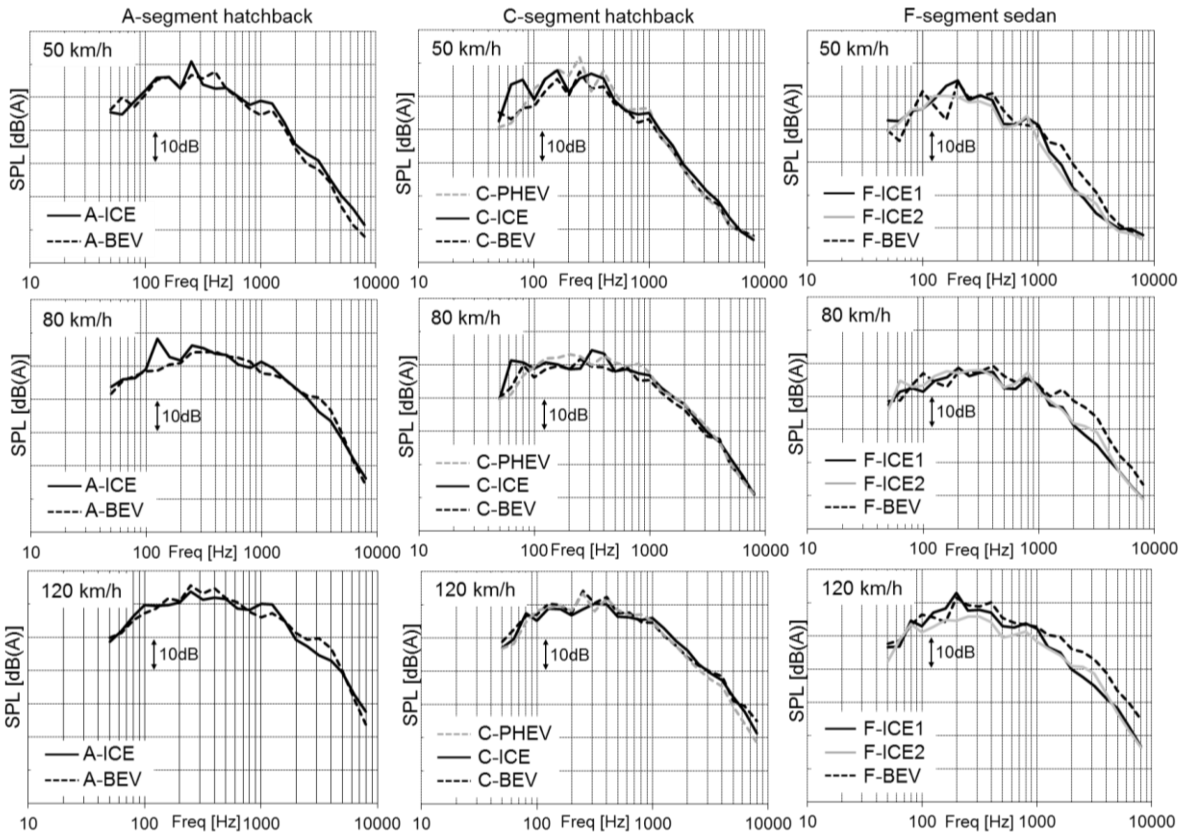

Fig. 5: Constant speed sound pressure level at front passenger position

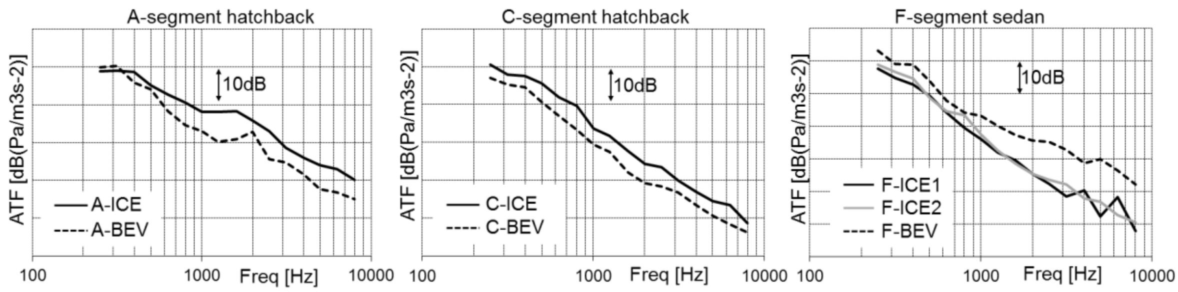

Fig. 6: Air-borne transfer functions from powertrain to driver

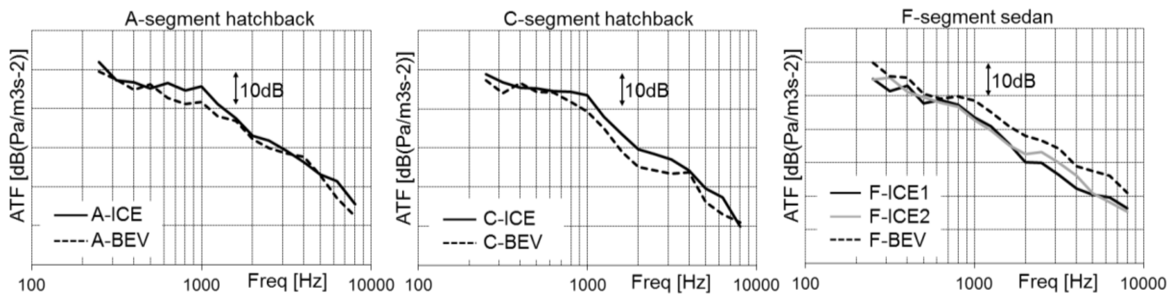

Fig. 7: Air-borne transfer functions from tyres to driver

The air-borne noise filtering performance from powertrain to driver of the tested cars can be seen in Fig. 6. The A and C-segment BEV models have better overall air-borne noise filtering performance than their respective ICE counterparts. That definitely gives a positive contribution to their better noise performance on road under WOT acceleration conditions. In the case of the A-segment BEV, some positive contribution is also given by the additional extended absorption treatment on the outer dash area (the ICE car outer dash is bare). The F-segment BEV is characterized by worse air-borne noise filtering performance than its conventional competitors. This seems mainly due to the fact that, unlike the BEV model, both ICE cars have a strong double wall partition between engine bay and passenger compartment, and fully extended absorption treatment in the engine bay.

The same considerations can be driven for the air-borne noise filtering performance of the tested vehicles from the tyres (Fig. 7). It is interesting to notice that, in addition to the heavy battery under the floor, the A-segment BEV has an extended underbody treatment (including the wheelhouse outer liners) with most of the surface having an acoustic function (over 40% of the total underbody area), while almost no underbody treatment is present on the ICE version (Fig. 8). Similarly, the C-segment BEV underbody surface is almost totally covered, with about 50% of the total underbody area being acoustically absorptive, while the ICE version, although largely covered, has almost no acoustic property.

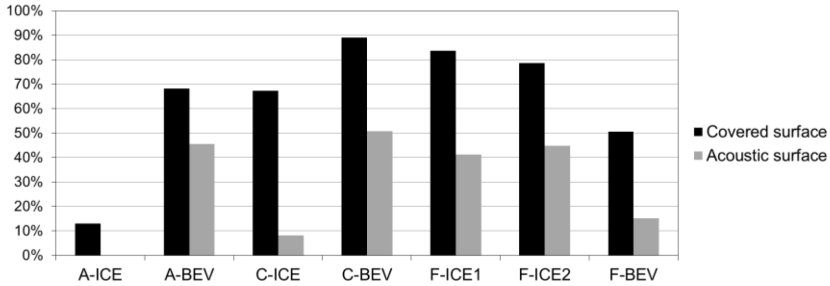

Fig. 8: Underbody coverage rates as a percentage of the total underbody surface

For the A and C segments, the tyres transfer function gap between BEV and ICE models is not as neat as for the powertrain, likely because of the additional exterior noise paths. This fact can also partly justify the similar performance of BEV and ICE models on road at constant speed.

On the other hand, the F-segment ICE vehicles carry an extended underbody treatment with a considerable amount of surface having an acoustic function (between 40 and 50% of the total underbody area), and perform clearly better than the BEV, which has a largely untreated and acustically reflecting underbody area, despite its large battery back mounted under the floor.

In conclusion, the test results show that cars with higher underbody coverage rates and larger acoustic surfaces perform better for tyre noise filtering performance, no matter the powertrain type.

Some interesting outcome can also be derived from the structure-borne transfer function test results from the powertrain (Fig. 9) and suspension (Fig. 10) mounts to the driver position, where it is possible to see the rather clear advantage that smaller segment BEV models have in comparison with their ICE counterparts.

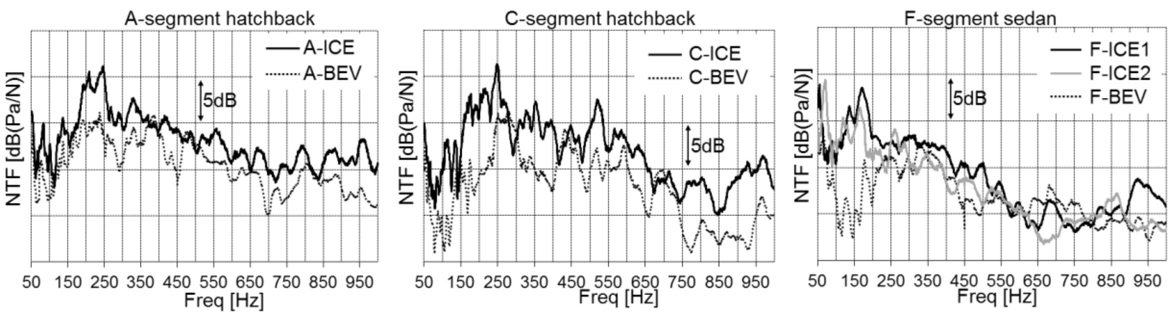

Fig. 9: Structure-borne transfer functions from powertrain mounts to driver

It looks reasonable to assume that this behaviour is driven by the battery pack under the vehicle floor, which seems to make a remarkable difference in terms of stiffness on less stiff bodies (typically belonging to lower segments). The same does not seem to happen on the high segment cars under test: although the BEV has some advantage for structure-borne noise filtering performance in the low frequency range, that goes quickly lost as the frequency increases, with ICE cars performing globally in the same range or even better than the BEV in the mid-high frequency domain.
It seems that the efforts spent by car makers on proper body design for these high segment ICE cars are successful, and the absence of the battery pack does not penalize their overall structural performance.

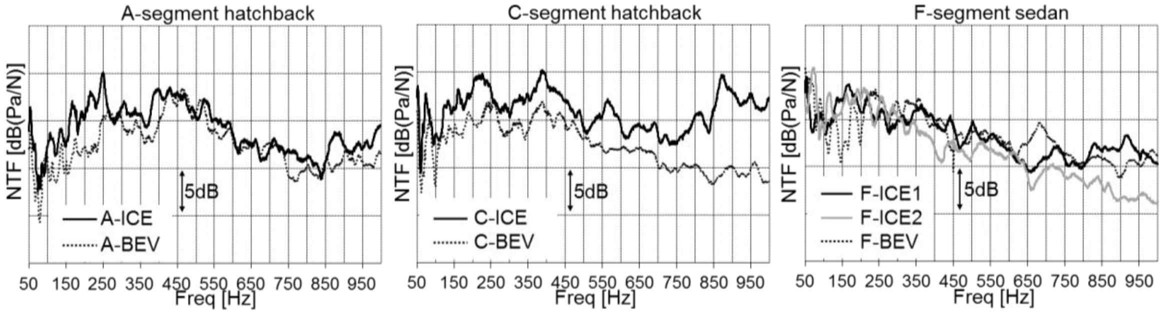

Fig. 10: Structure-borne transfer functions from suspension mounts to driver

4. Conclusions

After all, from the current market trends related to electrified passenger vehicles and the above car test results, it looks reasonable to foresee that in the very near future the NVH package of electrified cars is not going to undergo any major quick disruptions in comparison to the current state of the art of conventional powertrains.

This is partially due to the fact that hybrid vehicles are foreseen to drive a big part of the transition from conventional ICE towards purely electric mobility forecasted for the future, and for this kind of cars the possible modifications of the NVH package can be reasonably expected to remain at low levels due to the presence in any case of a conventional ICE powertrain.

Purely electric powertrains cause lower overall e-motor noise, however this is potentially not translating into less concerns for NVH engineers as the emission spectra and related user expectations could push the noise filtering performance from powertrain to interior compartment to higher levels versus current ICE vehicles.

In the long run and for BEVs, despite some possible reduction in the engine bay NVH package due to lower overall engine noise, there would be a real need for specific treatments against engine noise in the high frequency range (e.g. electric motor encapsulation, body-mounted absorbing treatments) and whenever the electric motor exhibits tonal components.

Additional concerns will further arise for tyre and aerodynamic noise, which in BEV models can lead to the same or even worse overall NVH performance at a given cruising speed than ICE vehicles in the same segment.

We have also seen that the underbody of battery electric vehicles can be more extensively treated than that of the same car with a conventional ICE powertrain. In addition to positive consequences for the vehicle noise filtering performance, this is also related to aerodynamic improvements and battery protection.

On top of the comparison among existing models shown in this paper, one should consider how BEV user's performance expectations will grow in the future, also linked to other trends like autonomous driving or attempts of OEMs to differentiate their offering in the BEV market, that could possibly push quietness requirements further to the next level, thus impacting on NVH efforts and countermeasures to be taken in next generation vehicles.

Last but not least, there are still uncertainties in the technical community regarding the subjective perception of BEV noise, mostly because of the lack of broadband noise coming from the conventional ICE engine and the consequent sudden unmasking of the noise coming from all other sources, in particular tyres and aerodynamics.

Further tests are required to gather deeper understanding, and more investigations are currently ongoing on newly introduced electrified vehicle models, including subjective NVH testing.

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