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# Sound quality analysis of the powertrain booming noise in a Diesel passenger car

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**Abstract**

Among many noises which can be heard inside a car, the booming noise caused by powertrain excitation is usually considered as one of the very annoying acoustic features that affect the interior sound quality of a car. This work presents results coming from an experimental analysis carried out on a Diesel passenger car in order to evaluate the interior booming sensation related with the engine rotation and firing. Tests were performed in acceleration conditions on the vehicle installed at the chassis dynamometer, by measuring noise at the driver and passengers' positions inside cabin. A waterfall analysis was firstly carried out to see the spectral and temporal pattern of recorded time-varying sounds. In particular, the change of sound level related to the fundamental frequency of engine firing and its harmonics was assessed as a function of engine revolution per minute at each microphone location. Acquired data were properly post-processed for sound quality analysis as well, in order to have information about the degree of booming sensation in the accelerating car and to quantify the level of annoyance perceived by each car's occupant. The analysis allowed to identify the vehicle operating conditions as well as the locations inside cabin that make the passengers more exposed to the booming phenomenon. The obtained results represent a useful starting basis for selecting the most appropriate noise and vibration control strategies in vehicle sound quality optimization process.


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*Keywords:* Vehicle Interior Noise; Booming Noise; Engine Excitation; Sound Quality.

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## 1. Introduction

The interior sound perceived in a car represents a fundamental factor in the development process of a vehicle. In order to align the product to customer expectations, a lot of efforts are usually accomplished by vehicle NVH engineers for improving the interior acoustical comfort. Surely, testing activity plays a crucial role in order to determine the current acoustical comfort and eventually, if particular NVH issues have been identified, improve vehicle design by selecting appropriate sound or vibration control strategies.

In a vehicle powered by an internal combustion engine, the NVH system having the most impact on the vehicle's overall acoustic image is with no doubt the engine. In general, the noise and vibration control from the engine to the passenger cabin has improved significantly over the years; therefore, the issue now is more about the quality of the sound of the engine than its noisiness. In order to obtain a desirable frequency balance and sound level in vehicle interior, Sound Quality engineering makes use of basic psycho-acoustic quantities which are known to accurately describe the pleasantness or annoyance sensations [1][2][3][4].

One of the engine-related acoustic effects which may considerably affect the acoustic comfort of the car occupants, is the powertrain booming noise. Automotive booming noise due to powertrain occurs when pure or narrow band tones related to the engine firing frequency and its harmonics excite, through various structural paths, the passenger cavity, inducing resonance effects and thus a prominent rise of acoustic pressure [5]. Booming noise can be then considered a low frequency interior noise strongly related to the structural-acoustic modal coupling of the vehicle [6]. The related sensation is usually considered as one of the very annoying acoustic features that influence the sound quality of the interior.

This work reports the results of an experimental investigation aimed to analyze the powertrain booming noise sensation in a Diesel passenger car. Tests were carried out in acceleration conditions on the vehicle installed at the chassis dynamometer, by measuring noise at the driver and passengers' positions inside cabin. In addition to transient tests, measurements involved also the execution of different constant speed conditions.

An accurate post-processing of the interior noise data in terms of order analysis and proper sound quality metrics allowed to evaluate the degree of powertrain booming sensation, identifying the locations inside passenger compartment much more affected by booming annoying phenomenon as well as the most critical vehicle operating conditions. The definition of the booming noise problem for the tested car represents a useful starting basis for the consequent root cause analysis and the selection of the most appropriate NVH control strategy [7].

**Nomenclature**

| | |
|---|---|
| EFR | Engine Firing Rate |
| $f_0$ | Engine firing frequency |
| k | Multiples of engine rotating frequency |
| ICP | Integrated Circuit Piezoelectric |
| N | Engine rotational speed |
| $N_{cyl}$ | Number of engine cylinders |
| NVH | Noise Vibration Harshness |
| OL | Overall Level |
| $\varepsilon$ | Integer equal to 1 (for a two-stroke engine) or 2 (for a four-stroke engine) |

## 2. Experimental activity

Experimental tests were carried out on a 4-cylinder 4-stroke diesel passenger car (category M1). Internal combustion engine (1461 cc) provides a maximum power of 55 kW and a maximum speed of 170 km/h. The car was installed on a chassis-dynamometer able to simulate vehicle inertia (1130 kg), aerodynamic and rolling resistance. In order to perform interior noise measurements the car cabin was equipped with eight microphones (ICP Class 1 pressure sensors), located at the height of driver and front/rear passengers ears' position. Figure 1 shows a schematic representation of the noise test setup. Acoustic signals were recorded at a sampling rate of 40960 Hz by using an LMS SCADAS multi-channel acquisition system which allows to trigger them with the tachometer signal containing the information about the engine rotational speed. Collected data were then properly processed in LMS Test.Lab software in terms of spectrograms, orders and psychoacoustic metrics.

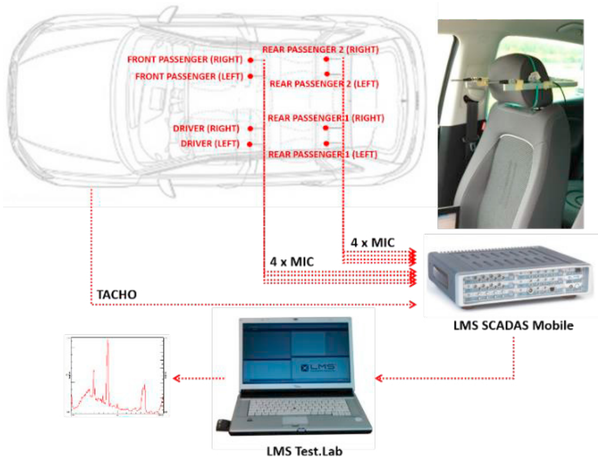


Fig. 1. Interior noise acquisition set-up.

Noise data were firstly acquired in 3rd gear during rapid partial throttle engine acceleration from about 1000 to 3000 rpm in approximately 20 sec. For a better understanding of the noise frequency content, different stationary operating conditions were also tested by varying vehicle speed from 10 to 130 Km/h at different gear ratios with an acquisition time of 60 sec for each condition. In particular, the investigated steady-states were: 10 km/h (1st gear), 20 km/h (1st gear), 30 km/h (2nd gear), 40 km/h (2nd gear), 50 km/h (3rd gear), 70 km/h (4th gear), 80 km/h (5th gear), 100 km/h (5th gear), 120 km/h (5th gear),130 km/h (5th gear).

## 3. Results and discussion

### *3.1. Waterfall and order analysis*

For a precise evaluation of the degree of booming sensation mainly associated with the engine activities, a waterfall analysis was firstly carried out in order to study the spectral and temporal pattern of the time-varying sounds, recorded during run-up condition at each microphone location inside cabin. Waterfall analysis allowed to identify the order-related spectrum-components which occur at locations proportional to the engine rotational speed. More in detail, the change of sound level related to the fundamental frequency of engine firing and its harmonics was analysed. The engine firing frequencies are usually expressed in terms of k-multiples of the rotating frequency, the so-called engine orders [8]:

$$f_o = k \cdot \frac{N}{60} [Hz] \tag{1}$$

where N is the engine rotational speed expressed in revolutions per minute (rpm).

Taking into account that the frequency related to engine firings, the so-called Engine Firing Rate (EFR), is defined as:

$$EFR = \frac{N}{60 \cdot \varepsilon} \cdot N_{cyl} [Hz] \tag{2}$$

where ε is an integer equal to 1 or 2 for a two-stroke or a four-stroke engine respectively, and $N_{cyl}$ represents the number of cylinders, according to formula (1), for the four-cylinder four-stroke engine powering the tested vehicle, the EFR corresponds to the 2nd engine order, as the frequency is two times (k=2) the engine's rotation one.

Figure 2 shows the spectrograms of the measured interior noise signals in front and rear microphones' positions. For brevity, the color-maps refer only to the left microphone location for each car occupant.

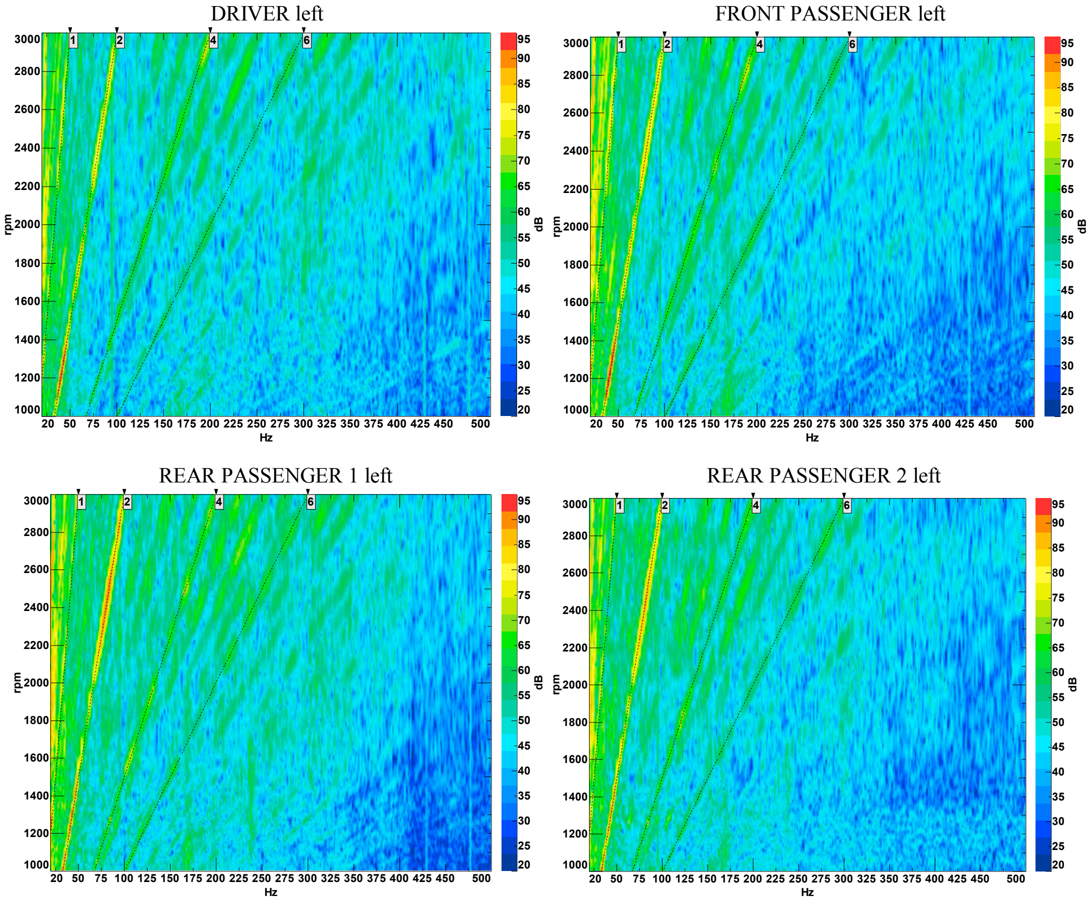


Fig. 2. 3D acoustic maps in engine run-up condition for front and rear internal microphones.

The major noise content is depicted at low frequency range up to 350 Hz. It is possible to observe that the pressure amplitude peaks of the spectrum are clearly distributed on the straight lines of the orders. As expected, the strongest peaks correspond to the 2$^{nd}$ engine order for all internal microphones. It is worth no note that higher pressure amplitude levels occur at the Engine Firing Rate when the engine revolutions range from approximately 1100 up to 1500 rpm, especially for the front measurement locations inside cab. Besides, for the rear positions high noise levels characterize the 2$^{nd}$ engine order also when the engine sweeps through the range 2200 to 3000 rpm. As no substantial differences can be found among the front internal microphones, as well as among the rear ones, in the following for sake of brevity the booming noise analysis will refer only to the driver and the rear passenger #1 (see Figure 1).

Figure 3 shows the results of the order analysis. Overall noise level and main orders (2$^{nd}$, 4$^{th}$ and 6$^{th}$ harmonics) are reported as a function of engine rotational speed for the left and right ear positions of driver and rear passenger. Only slight differences in the orders trend can be observed between the left and right ear locations. Moreover, it is immediate to note how the sound level of the 2$^{nd}$ harmonic component dominates the overall magnitude of interior noise for both driver and rear passenger. This result further confirms the outcomes of the previous waterfall analysis. The 2$^{nd}$ engine order considerably affects the overall noise level when vehicle speed ranges from approximately 1100 to 1500 rpm as well as from 2200 to 3000 rpm. In particular, when the engine sweeps through this latter rpm range, the passenger in the rear seat seems to be most affected by the pressure rise in the car cavity.

Therefore, from an initial analysis, for this car the 2$^{nd}$ engine order results the most important in the booming sensation. However, it is difficult to find a direct correlation between the results of the order analysis and the booming phenomenon, as the overall sound pressure level cannot sufficiently express the perceptual feeling. In order to provide information about the level of sound annoyance caused in passenger compartment by booming phenomenon, some psychoacoustics-based indices can be rather used. In the next paragraph the results of the sound quality analysis are presented.

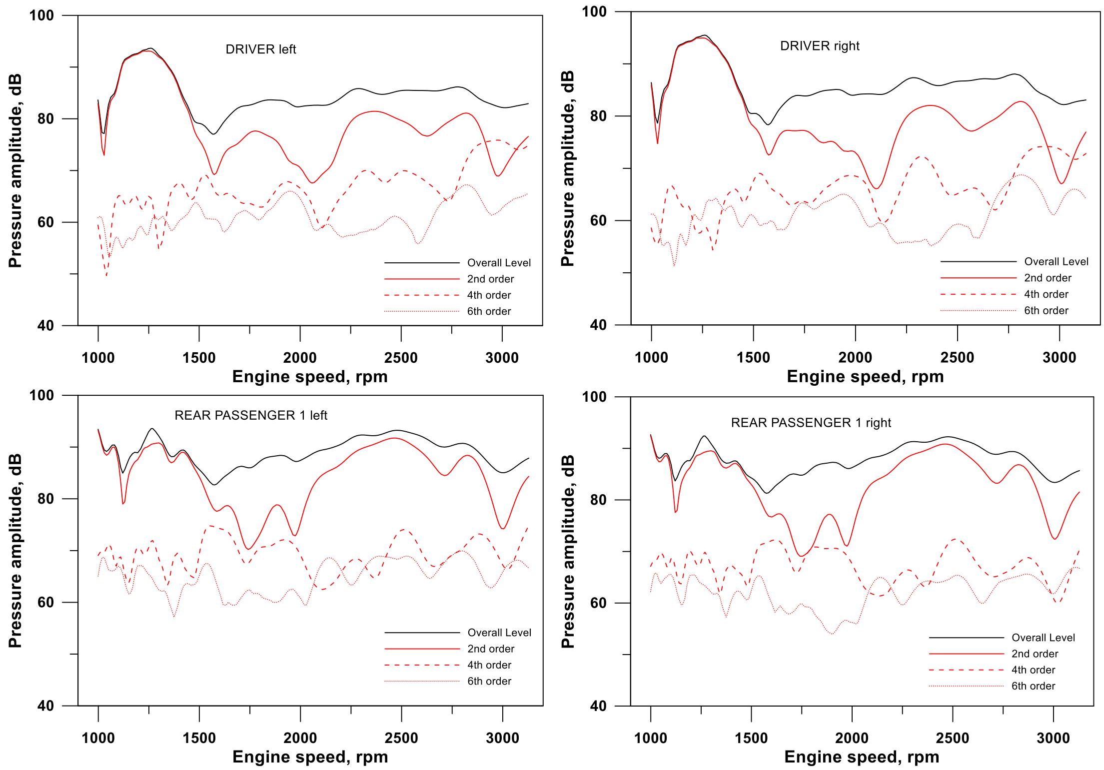


Fig. 3. Overall Level and orders trend during car acceleration at left/right ear of driver and rear passenger.

### *3.2. Sound quality analysis*

Among all the most common sound quality metrics widely used in automotive industry, Loudness is usually regarded as the most important metric able to describe the perceptual feeling associated with the booming noise [5]. It is related to the magnitude of sounds and takes into account the filtering characteristics of human auditory sense in time and frequency domains. For non-steady-state noises as those acquired in vehicle dynamic conditions, particularly useful is the Time-Varying Zwicker Loudness [2], which is calculated in compliance with DIN 45631/A1 [9].

In Figure 4, the Time-Varying Loudness at the driver and rear passenger positions, during vehicle acceleration, is reported as a function of engine rotational speed. As it is possible to note the metric at driver ears location shows strong deviations of up to 5 sones from the ideal trend, in particular in the range between 1100 and 1500 rpm. An even higher amplification (up to 8-9 sones) occurs at the rear passenger position when the engine sweeps through the engine rotational speed range 2200 ÷ 2700 rpm, and it is followed by a significant level reduction in the next rpm range (around 2750 rpm) and another successive increase around 2850 rpm. Therefore, the overall impression of this vehicle is not characterized by a smooth and refined ride, as the sound signature does not grow linearly with the engine rotational speed [10]. The vehicle acoustic image rather results very "boomy".

In order to better define the annoyance level due to booming phenomenon and how the related low frequency pressurizing feeling changes from front to rear positions inside cabin, also the evaluation of the Sharpness metric, strongly related to the spectral content of the noise, could be useful. Sharpness sensation is a measure of the proportion of the high frequency content of a sound and can be calculated using Zwicker and Fastl's approach [2], based on the specific Zwicker Loudness.

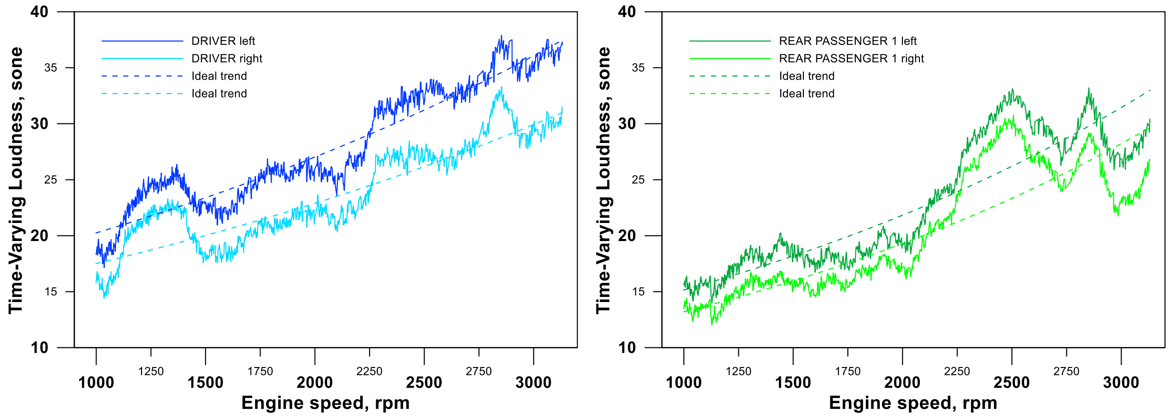


Fig. 4. Time Varying Loudness vs. RPM at driver and rear passenger location during vehicle acceleration.

In Figure 5 the Sharpness index is reported for the two considered passenger positions. It is possible to note that the Sharpness values for the driver are higher than those measured at the rear passenger ears. This indicates a greater proportion of high frequency content of the noise measured in the front position with respect to that in the rear one.

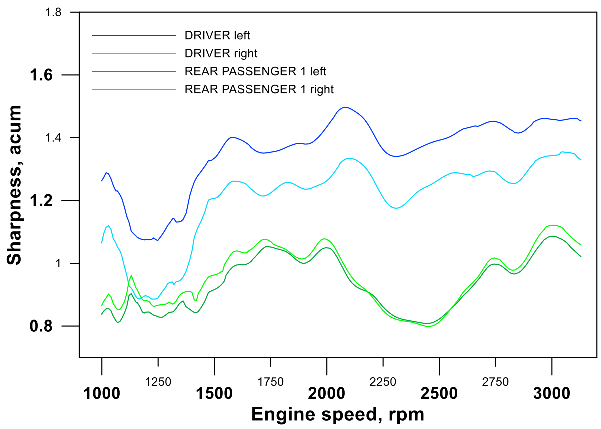


Fig. 5. Sharpness vs. RPM at driver and rear passenger location during vehicle acceleration.

To give evidence of this, in Figure 6 a comparison between the noise spectra up to 5000 Hz of the left microphones signals at driver and rear passenger positions is reported. The frequency spectra refers to the 2820 rpm condition during vehicle acceleration. From the graph it is evident that the 'DRIVER left' microphone measures higher pressure amplitudes in the frequency range above 350 Hz, with respect to the rear one.

As a consequence, in order to better evaluate powertrain booming sensation at the different positions inside cabin, establishing a more valuable Loudness comparison among front and rear positions, the partial Loudness below 200 Hz should be assessed. As a matter of fact, different research works demonstrated that partial Loudness below 200 Hz shows higher correlation with booming sensation than overall Loudness [11][12][13].

A low-pass filter characterized by a cut-off value of 200 Hz was then implemented in LMS Test.Lab environment and applied to the acoustic signals in the time domain. New Time-Varying Loudness values taking mainly into account the effect of firing frequency only, were then calculated, as shown in Figure 7.

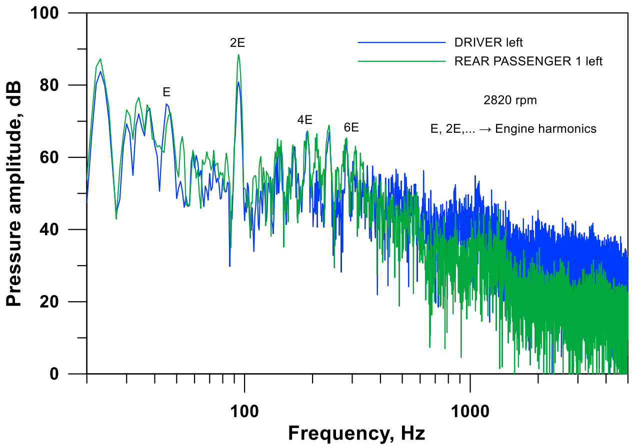


Fig. 6. Noise spectra at driver and rear passenger left ear location @ 2820 rpm.

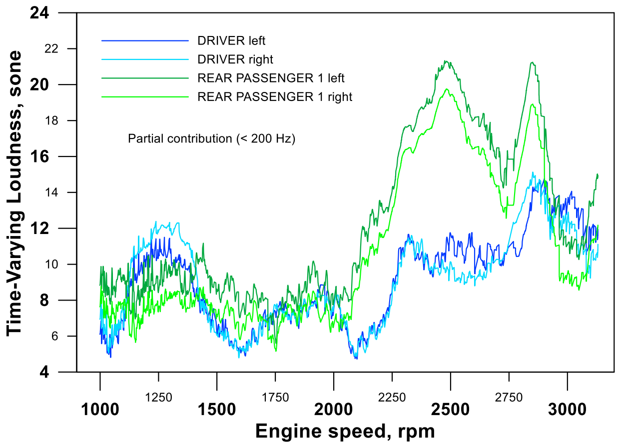


Fig. 7. Partial Time-Varying Loudness (below 200 Hz) vs. RPM during vehicle acceleration.

By observing the new Loudness trends, it is possible to note that at low engine speeds, in the range between 1100 and 1500 rpm, the driver results slightly more affected by the powertrain booming noise. Moreover, in the range 2200 ÷ 3000 rpm, the perception of the booming phenomenon becomes prominent for the passenger in the rear seat, who feels sound intensity up to 8 sones higher than the driver.

Analyzing results also for the other two car occupants, not reported in the paper for brevity, it can be finally stated that the rpm range 2200 ÷ 3000 rpm represents the most critical engine operating conditions, which make the passengers in the rear seats exposed more than any other to the booming annoying sensation. It is worth to note that in cruise conditions, if the engine speed reached one of the critical range values, the most annoying booming sensation would occur. To confirm this, in Figure 8 the noise spectra at driver and rear passenger left ear location at 130 km/h in 5$^{th}$ gear stationary vehicle condition show that the pressure amplitude level at the engine firing rate (2$^{nd}$ engine order) in the rear position is much higher (of approximately 14 dB) than the driver one.

Hence the identification of an appropriate control strategy would be desirable. In this sense, further investigations will regard the implementation of an acoustic finite-element (FE) model of the interior car cabin for determining its acoustic resonance frequencies. The model will be useful also for understanding the spatial pattern of each modal shape, and in particular the pressure minima and maxima areas in vehicle acoustic cavity. Then, crossing interior noise data acquired in dynamic and stationary conditions with the information about the acoustic modes and their spatial pattern, it will be possible to identify the frequencies of the acoustic cavity modes to be decouple from the engine excitation in order to reduce the annoying booming sensation perceived by passengers in the rear seats.

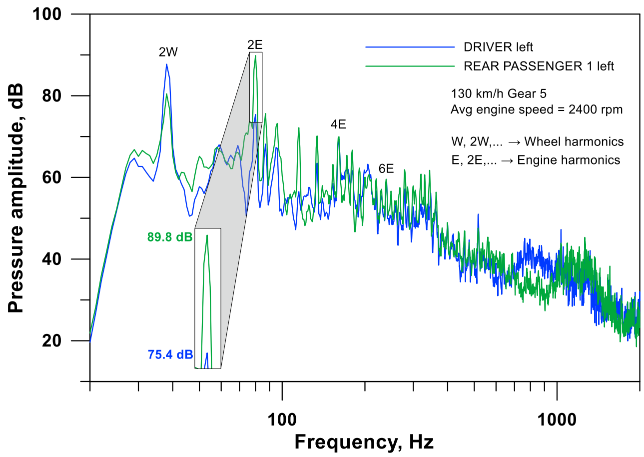


Fig. 8. Noise spectra at driver and rear passenger left ear location @ 130 km/h - gear 5 steady-state condition.

## 4. Conclusion

One of the major NVH refinement issues in the automotive industry regards the sound quality of the cabin noise. Significant efforts have been done in order to make the perceived noise inside passenger compartment increasingly pleasant to the customer. With this aim, in this work, the booming noise sensation caused by powertrain excitation in a Diesel passenger car was experimentally characterized. Dynamic and steady-state measurements were carried out on the vehicle installed at the chassis dynamometer, by measuring noise at the driver and passengers' positions inside cabin. Results obtained through an accurate analysis of the main orders and some sound quality metrics allowed to identify the most critical engine operating conditions, as well as to notice a much higher degree of booming sensation perceived by passengers in the rear seats. The next stage will regard a detailed root cause analysis for understanding the mechanism of generation of the identified NVH issue, then to finally select the most appropriate NVH countermeasure. In addition, a more extensive study will be carried out, investigating the effects on the interior booming sensation of other possible causes such as the road excitation and the wind fluctuation.

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