Evaluation of Noise Level Inside Cab of a Bi-Fuel Passenger Vehicle

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Abstract: - It is well known that the vehicle interior noise comfort is one of the main target which may attract customers for purchasing a vehicle. Eventually, the amount of discomfort depends on magnitude, frequency, direction and, as well as, on the duration in vibration exposition inside the cabin. The comfort of the driving strongly influences the driving performances. Generally, the acoustic noise exposition depends on two main sources: engine and powertrain systems and interaction between tyre and road surface. In this paper, the sound quality assessment of a bi-fuel passenger car tested over a chassis-dynamometer bench at different vehicle operating conditions, will be analyzed. The main target of the study is to measure the perceived noise inside cabin for different vehicle speed conditions assessing the influence of the investigated operating conditions on the driver's acoustic comfort.

Key-Words: - Acoustic Cavity, Interior Noise, Loudness, Sharpness, Sound Quality, Vehicle

1 Introduction

Nowadays noise and vibration are considered two of the most important quality factors in vehicle design.
For this reason in recent years automotive industries have increased their interest in vehicle NVH refinement.
While vehicle exterior noise is led by noise pollution legislation, customer's satisfaction and acceptance play a key role for the noise and vibration characteristics inside the vehicle [1]. Excessive noise and vibration, in fact, induce in driver and passengers stress, fatigue and feelings of insecurity, reducing comfort and significantly affecting the vehicle's overall image.
Noise and vibration generation derives from systems such as the engine [2][3][4], pumps, drivetrain, wheels and tyres, or may be caused by system integration problems, related to the matching between powertrain and body and between chassis and body. Controlling vibration and noise in vehicles represents a severe challenge to designers and means setting targets to be reached in order to ensure vehicle success in the marketplace.
Vehicle noise and vibration targets consist of interior and exterior targets. Interior targets, in particular, include the whole-vehicle and single-component noise targets inside the vehicle cabin and ride quality (vibration) targets at different operating conditions.
Reducing the level of interior noise is extremely important for the acoustic comfort of driver and passengers, however another important factor to be taken into account is the quality of sound in the cabin. Over recent years many studies have been conducted in order to make vehicle interior noise not just quiet but also pleasant.
The paper presents some of the results coming from an experimental campaign carried out on a bi-fuel passenger car, tested over a chassis-dynamometer bench for evaluating noise and vibration characteristics in addition to exhaust gaseous emissions and main engine parameters, [5].
Specifically, for the aim of present work only results related to measurements of noise perceived in vehicle cabin will be deeply analyzed, assessing the influence of the investigated operating conditions on the driver's acoustic comfort and considering some of the most commonly used parameters for sound quality analysis.

2 Experimental Setup

Experimental tests were executed on a Euro 4 commercial bi-fuel (gasoline/natural gas) passenger car installed on a chassis-dynamometer to simulate the right dynamic road load resistance and vehicle inertia (1130 kg). Main characteristics of the tested vehicle's engine are reported in Table 1.

Model	Bi-fuel Gasoline/CNG, 4 strokes	
N. of cylinders	4	
Displacement	1242 cm^3	
	Gasoline	CNG
Maximum Power	44 KW @5000rpm	38 KW @5000rpm
Maximum Torque	102 Nm @3000rpm	88 Nm @3000rpm

Table 1: Main features of the tested vehicle's engine

For this investigation, acoustic pressure measurements were taken inside the vehicle cabin at the driver's left and right ears location using conventional microphones (Microflown Class 1 ICP microphones) for the evaluation of the resulting sound quality. The acquisition recording time was 60 seconds per run performed with the vehicle driven and motored on a 4-wheel-drive dynamometer.
Table 2 presents a list of the considered stationary conditions for testing vehicle in gasoline operating condition. In particular, measurements were performed by varying vehicle speed from 10 to 70 Km/h at different gear ratios.
Taking in account that possible variations of the gas pedal angle could occur during the acquisition time, tests were executed twice for each investigated condition and mean results have been considered for post processing. Thus, data are here reported as mean values over the two different tests in all 60 seconds of acquisition time.

	Speed [Km/h]	**Gear**	**Engine Speed [rpm]**
Case 1	10	1	1458
Case 2	20	2	1577
Case 3	30	2	2360
Case 4	40	2	3118
Case 5	40	3	2133
Case 6	50	3	2676
Case 7	60	3	3229
Case 8	60	4	2442
Case 9	60	5	1969
Case 10	70	3	3757
Case 11	70	4	2830
Case 12	70	5	2285

Table 2: Tested steady-state conditions

Beside steady-state tests, transients were carried out. In particular, the continuous acceleration between 1000 to 3500 rpm in third gear was analyzed.
During the execution of the experimental tests exhaust pollutant emissions were measured by using a portable emission measurement device (Semtech-D by Sensors), able to measure volumetric concentrations of CO, CO_2, THC, NO and O_2. CO and CO_2 are measured throughout Non-Dispersive Infrared detector, THC by Flame Ionization detector, NO by Chemiluminescence and O_2 by chemical sensor. A carbon balance was applied for fuel consumption estimation. Moreover, the analyzer is connected to a mass flow rate sensor (Pitot tube) for measuring exhaust flow and temperature, and to an On-Board Diagnostic interface for monitoring main engine parameters, such as engine speed, spark advance, load, injection time.
Fig. 1 shows a schematic representation of the noise test setup, where it is possible to note the presence of the two internal pressure transducers fixed on the driver seat at his head height, an external pressure microphone for measuring exhaust noise emissions, and an accelerometer sensor for acquiring engine block vibrations. All the sensors were connected to a multi-channel acquisition system (LMS SCADAS III), which in addition to contemporarily record acoustic and vibrational signals, allowed to trigger them with the tachometer signal containing the information about the engine rotational speed. Data were then post-processed in terms of frequency spectra and Overall Noise Level by using LMS Test.Lab software.

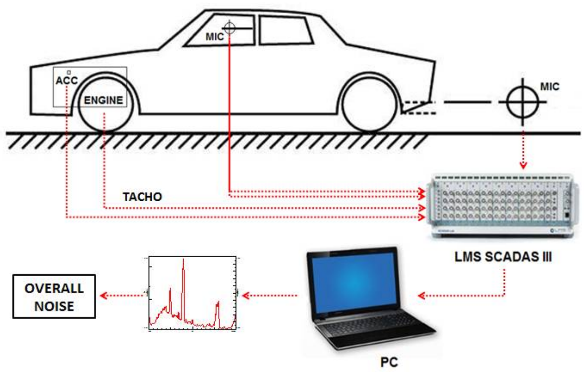


Fig. 1: Noise and vibration experimental setup.

As the main objective of present work is to study and analyze vehicle interior sound quality, in the next paragraph only results related to noise signals acquired by the two internal microphones will be reported and discussed in detail.

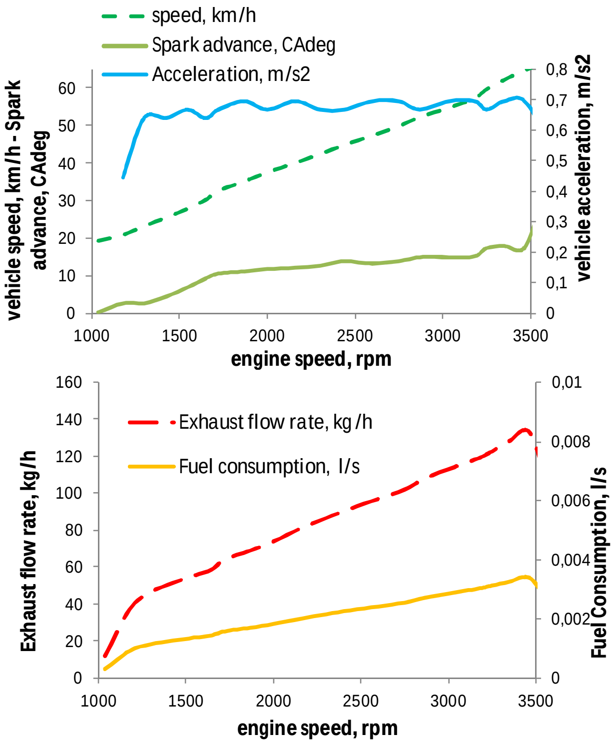
3 Results Analysis

Over the years, great attention on the problem of isolation of the passenger cabin from the engine, has been paid. Therefore, an important issue regards the quality of the sound of the engine and its transmitted noise inside the cabin, [6].

The two main sound quality criteria for the powertrain are:

- Max Loudness (or A-weighted sound pressure level) for overall noise and main engine orders (firing frequency and its first few even, odd and half-integer multiples), at idle and in hard and slow acceleration conditions.
- Linearity of overall noise and engine orders (the linear growth with the RPM, with no significant peaks and valleys).

In Fig. 2, the main engine/vehicle parameters and the time-varying Loudness at the driver position, during a vehicle acceleration carried out on the chassis dynamometer, are reported as a function of engine speed. The upper plot reports the vehicle speed and acceleration and the spark-advance. The analyzed acceleration goes from 20 to 65 km/h in the range 1000-3500 rpm and is quite constant with the exception of the starting phase where a steeper increasing is visible. Exhaust flow rate and fuel consumption, both reported in the middle diagram, show a continuous increasing. Fuel consumption varies between 1 and 3 ml/s in the analyzed speed range, [7]. In the bottom plot red and green curves represent left and right ear Loudness, respectively.



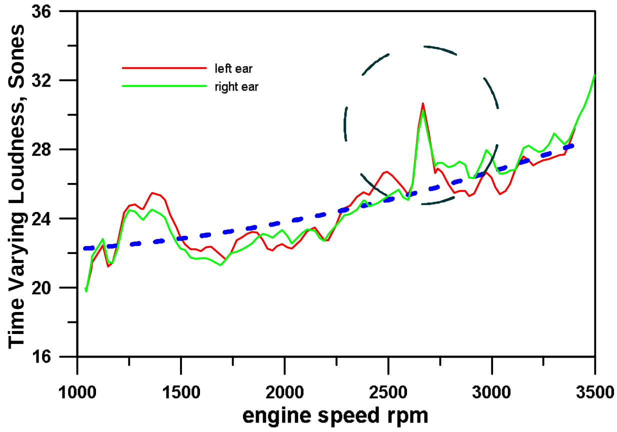


Fig. 2: Main engine parameters and Time Varying Loudness vs. RPM during vehicle acceleration.

The circle line, depicted in Fig. 2, in the range between 2500 and 3000 rpm, shows strong deviations of up to 5 sones from the ideal trend (dashed blue line). As it is possible to note, the overall level expressed by time-varying Loudness, exhibits a strong amplification as the engine sweeps through a certain engine rotational speed range (2500 ÷ 3000 rpm), and a significant increased level in the range 1200 ÷ 1500 rpm. It can be stated that the overall impression of this vehicle is to be very "dull".

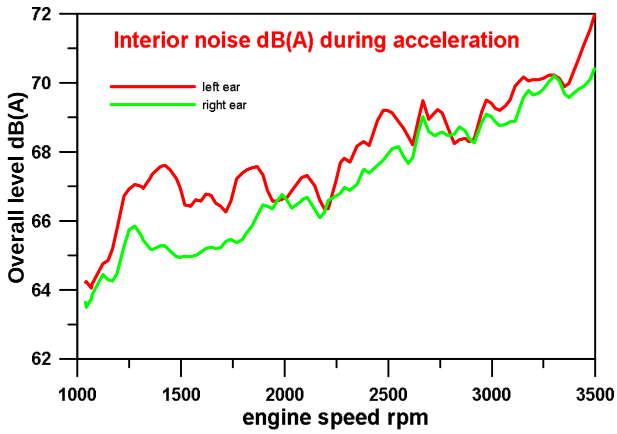


Fig. 3: Overall noise level in dB(A) vs. RPM (left ear: red curve, right ear: green curve).

In Fig. 3 the A-weighted overall level vs. rpm engine speed, for the left and right driver ear (red and green line, respectively), is reported. At about 2600 rpm the noise level increases and to better define the sound quality in Fig. 4 the sharpness index is also reported. Only left driver ear curve is shown, as no substantial differences between this latter and the right one have been found.

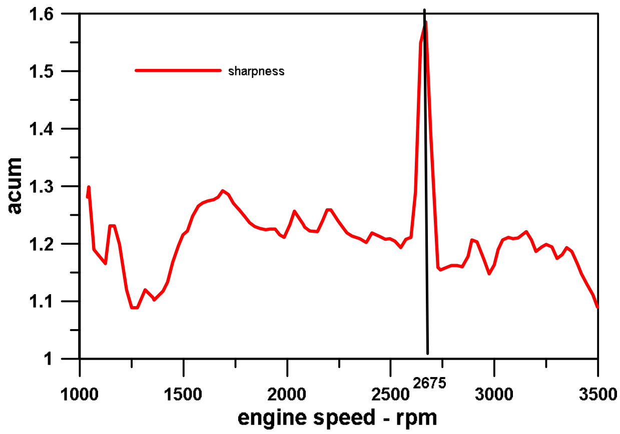


Fig. 4: Sharpness vs. RPM.

The opposite sensation to the pleasantness of a sound is its "sharpness" allowing to classify sounds as shrill (sharp) or "dull". The sharpness sensation is strongly related to the spectral content and center frequency of narrow-band sounds. The sharpness is an important measure that takes into account the frequency content of the noise. It is defined as the ratio between the high frequency noise level and the overall level and it is not related to sound intensity, but it results to be high for metallic noise components that are generally annoying and correlated with bad quality of the vehicle, [1].
The sharpness is expressed in the unit "acum". The reference sound of 1 acum is a narrow-band noise, one critical band wide, at a center frequency of 1 kHz and having a level of 60 dB.
By observing Fig. 4, it is possible to note that the maximum sharpness peak is at 2675 rpm. In order to have more information about the frequency content of the noise spectrum, in Fig. 5 this particular condition is reported. By carefully studying the frequency content of the acquired signals it is possible to identify the typical frequencies at which strong excitations occur due to cylinder firings, namely the Cylinder Firing Rate (CFR) and the Engine Firing Rate (EFR). Comparing frequency spectra of the right and left pressure microphones signals, no substantial differences have been noted.
Table 3 summarizes the information extracted from the left and right microphones spectra analysis, in all the tested stationary vehicle conditions. More attention has to be paid to the conditions characterized by a speed of 50 Km/h in 3rd gear, and of 70 Km/h in 4th and 5th gear, at which both left and right noise spectra present a peak corresponding to a frequency of 33 Hz, whose value is higher or slightly lower than the CFR one.

Speed [Km/h]	Gear	Engine Speed [rpm]	CFR [Hz]	EFR [Hz]	Peak Frequency [Hz]	Peak Value Left Mic. [dB]	Peak Value Right Mic. [dB]
10	1	1458	12.2	48.6	-	-	-
20	2	1577	13.1	52.6	-	-	-
30	2	2360	19.7	78.7	-	-	-
40	2	3119	26.0	104.0	-	-	-
40	3	2133	17.8	71.1	-	-	-
50	3	2676	22.3	89.2	33	71	70.5
60	3	3230	26.9	107.7	-	-	-
60	4	2442	20.4	81.4	-	-	-
60	5	1969	16.4	65.6	-	-	-
70	3	3757	31.3	125.2	-	-	-
70	4	2830	23.6	94.3	33	71.7	70.8
70	5	2286	19.0	76.2	33	73.6	72.3

Table 3: Characterization of the frequency spectra of left and right driver microphones signals.

This is easily visible by viewing Fig. 5-7, which report the frequency spectra up to 100 Hz of the left and right driver microphones signals for the latter particular conditions.

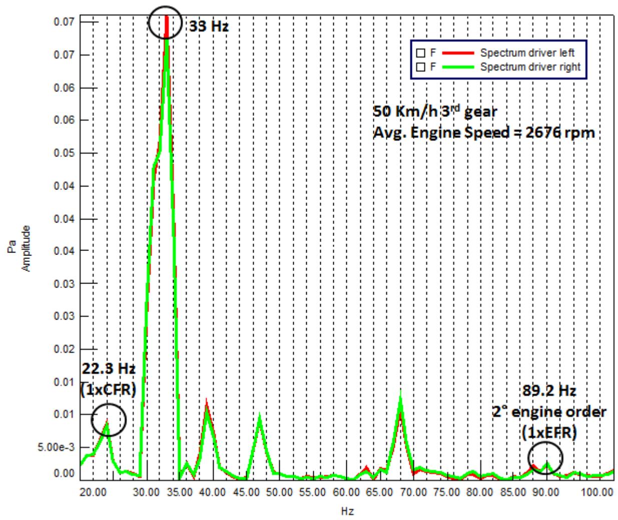


Fig. 5: Left and right driver noise frequency spectra @ 50 Km/h – 3rd gear condition.

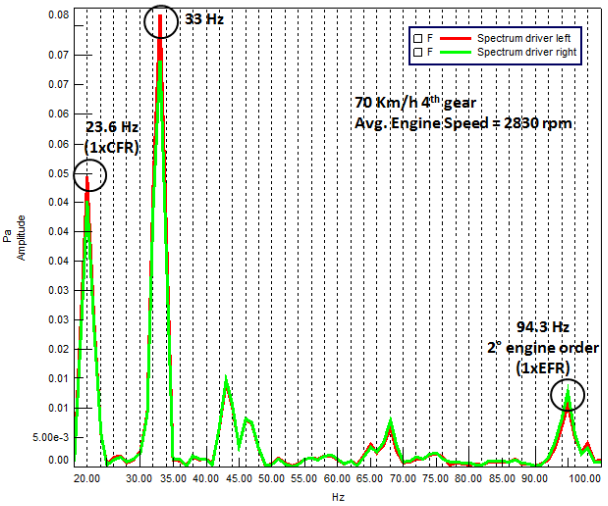


Fig. 6: Left and right driver noise frequency spectra @ 70 Km/h – 4th gear condition.

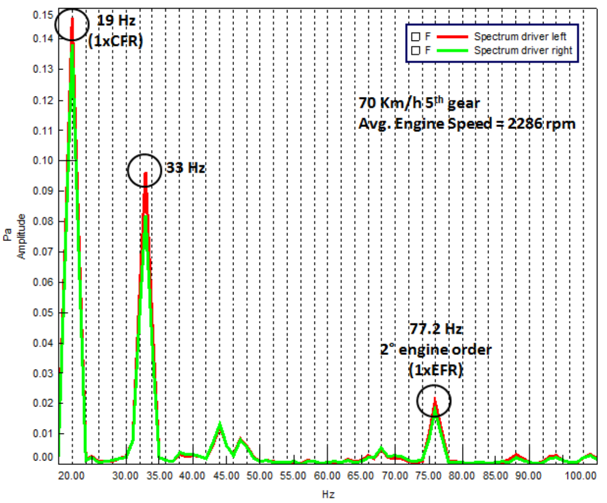


Fig. 7: Left and right driver noise frequency spectra @ 70 Km/h – 5th gear condition.

It is important to underline that for the first two particular conditions the higher noise level is at the frequency 33 Hz, that for the investigated engine speeds represents the half integer multiple firing frequency.

Fig. 8 reports exhaust flow rate, spark advance and CO_2 emissions as a function of engine speed, for all the tested steady-states.

Red points highlight the three conditions indicated above (50 Km/h in 3rd gear, and 70 Km/h in 4th and 5th gear).

Both exhaust flow rate and CO_2 emissions increase when engine speed increase, [8]. Spark advance, instead, is less variable. The critical conditions for internal vehicle noise do not seem to be affected by measured exhaust and engine parameters.

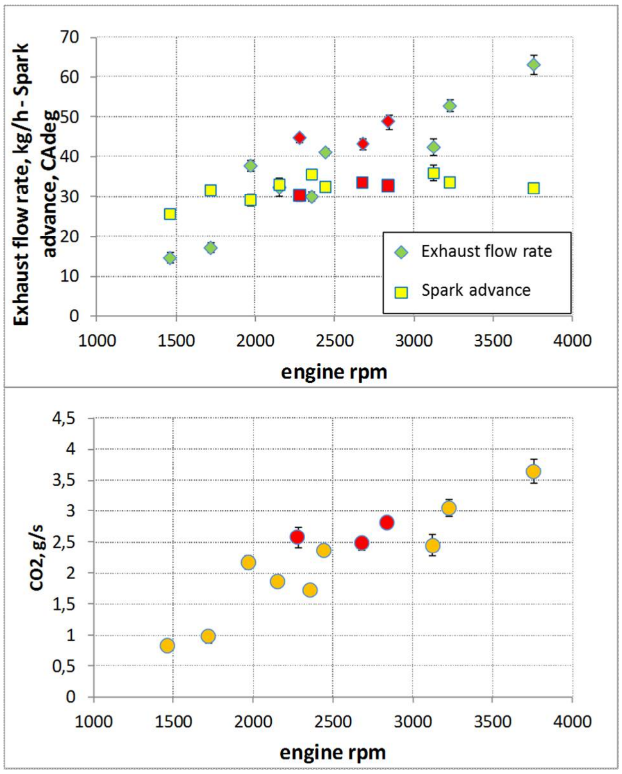


Fig. 8: Exhaust flow rate, spark advance and CO_2 emissions over the steady-states.

For a complete results analysis, Overall Noise Level expressed in dB and in dB(A), has been assessed too, for all the considered operating conditions and for both transducers (see Table 4).

Speed [Km/h]	Gear	Engine Speed [rpm]	Left Microphone OL [dB]	Left Microphone OL [dB(A)]	Right Microphone OL [dB]	Right Microphone OL [dB(A)]
10	1	1458	79.9	64.4	79.8	64.2
20	2	1577	79.1	64.2	79.1	64
30	2	2360	83.3	66.1	83.1	64.7
40	2	3119	86.4	67.1	86.7	67.4
40	3	2133	86.6	65.6	87.1	65.8
50	3	2676	92	66.7	92.2	66.2
60	3	3230	87	67.9	86.7	68.1
60	4	2442	86.3	66.6	85.7	66.8
60	5	1969	86.8	66.3	87.1	66.8
70	3	3757	90.5	70.9	90.3	71.2
70	4	2830	92.2	68.2	91.8	68
70	5	2286	91.9	67.6	91.2	67.8

Table 4: Overall Noise Level in dB and dB(A) of the left and right microphones signals.

As expected, Overall Level expressed in dB assumes the higher values in correspondence of the three conditions identified as the most critical. This

is likely due to the presence of the non-negligible amplitude peak at the frequency of 33 Hz.
In terms of sound quality perception the vehicle under test exhibits deviations of about 5-6 sones from its mean acceptable noise value, representing a loud vehicle in respect of a vehicle whose noise behavior increases linearly with rpm engine and vehicle speed. This particular effect is called "boom" by vehicle engineers. Typically, the most annoying occurrences of boom are at steady state – at idle or cruise condition, when the frequency of excitation from the engine aligns or is very close to an acoustic cavity mode, [6].
It is well known that the main cause of boom during vehicle acceleration is the excitation of the engine at its firing frequency, which is transmitted from engine and/or exhaust to vehicle body panels exciting successively possible acoustic cavity resonances. Generally, to compute acoustic frequencies, an acoustic finite-element approach is necessary. Nevertheless, in order to get a quick estimation of vehicle cavity frequencies, a very simple formula developed for small-room acoustics [9], can be used:

$$f_{l,m,n} = a_c \left[\left(\frac{l}{2l_x} \right)^2 + \left(\frac{m}{2l_y} \right)^2 + \left(\frac{n}{2l_z} \right)^2 \right]^{1/2} \quad (1)$$

where l_x, l_y and l_z, represent the x, y and z dimensions of the parallelepiped system as assumed the vehicle, a is the sound velocity with the subscript c that denotes the flow state inside the enclosure, and l, m and n are arbitrary integers ≥ 0.

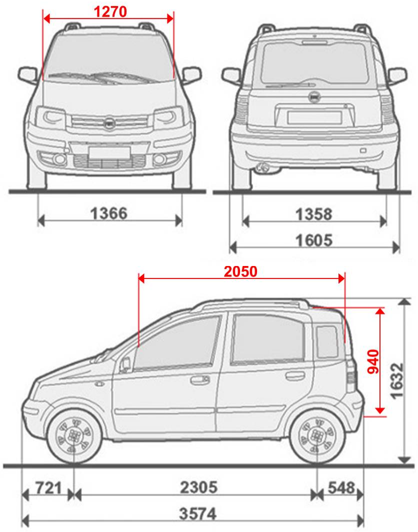


Fig. 9: Dimensions expressed in millimeters of vehicle under test.

Applying formula (1) to the tested vehicle internal volume, whose dimensions in millimeters along x, y and z directions are indicated in red color in Fig 9, the first natural acoustic mode, that is the first longitudinal mode (along the major dimension), has been found at a frequency of about 84 Hz, which is much higher than the 33 Hz frequency band.
Thus, further experimental analyses are necessary, in order to verify if vehicle's operation at the identified critical conditions may excite any natural structure mode.

4 Conclusion

One of the major development issues for the automotive industry is the automotive cabin noise. In the research panorama, significant efforts have been done in order to reduce both sound levels and to improve sound quality for making the sound pleasant to the consumer. With this aim, in this paper the influence of the interior noise of a car on driver comfort, was experimentally analyzed. The experimental campaign has been realized on a dynamometer chassis test bench in steady state conditions and in run up condition, as well. The results have shown a noisy vehicle for some particular vehicle speeds. Further analyses with particular regard to structure vibration are necessary to better understand such behavior. Contemporarily, a future experimental campaign could be carried out on the road in order to have information about the real passengers noise perception during urban cycles and as well as the overall CO, NO_X, and PM2.5 concentrations inside the cab.

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