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Acoustic and psychoacoustic levels from an internal combustion engine fueled by hydrogen vs. gasoline

Miguel Arana [a,*], Ricardo San Martín [a], José Carlos Urroz [b], Pedro M. Diéguez [b], Luis M. Gandía [a,*]

[a] Institute for Advanced Materials and Mathematics (INAMAT[2]), Departamento de Ciencias, Universidad Pública de Navarra (UPNA), Arrosadia Campus, 31006 Pamplona, Spain
[b] Departamento de Ingeniería, Universidad Pública de Navarra (UPNA), Arrosadia Campus, 31006 Pamplona, Spain

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ABSTRACT

Whereas noise generated by road traffic is an important factor in urban pollution, little attention has been paid to this issue in the field of hydrogen-fueled vehicles. The objective of this study is to analyze the influence of the type of fuel (gasoline or hydrogen) on the sound levels produced by a vehicle with an internal combustion engine. A Volkswagen Polo 1.4 vehicle adapted for its bi-fuel hydrogen-gasoline operation has been used. Tests were carried out with the vehicle when stationary to eliminate rolling and aerodynamic noise. Acoustics and psychoacoustics levels were measured both inside and outside the vehicle. A slight increase in the noise level has only been found outside when using hydrogen as fuel, compared to gasoline. The increase is statistically significant, can be quantified between 1.1 and 1.7 dBA and is mainly due to an intensification of the 500 Hz band. Loudness is also higher outside the vehicle (between 2 and 4 sones) when the fuel is hydrogen. Differences in sharpness and roughness values are lower than the just-noticeable difference (JND) values of the parameters. Higher noise levels produced by hydrogen can be attributed to its higher reactivity compared to gasoline.

1. Introduction

Renewable hydrogen is a sustainable solution for decarbonizing the energy system, reducing pollutants emissions to the environment and climate change mitigation. For these reasons, it is receiving a strong institutional and business boost as a future energy vector and fuel, especially in the European Union (EU) [1–2]. Therefore, progressive substitution of current fossil fuels with renewable hydrogen is a highly desirable scenario. Direct use of hydrogen as fuel of internal combustion engines (ICEs) is an active area of research, complementary to other possible applications of hydrogen in the transport sector such as to fed fuel cells or to synthesize hydrocarbon fuels.

The main sector that will presumably use this fuel is transport, a sector with high energy demand. Currently, most of the world's transportation relies on alternative ICEs powered by petroleum-derived fuels. As for the road transport, its importance in the EU is demonstrated by the facts that more than 18.5 million vehicles were 'made in Europe' in 2019, representing 20% of global vehicle production—5.6 million of these vehicles were exported around the world—and there are 313 million vehicles in circulation on Europe's roads today [3]. The automotive sector provides jobs for 14.6 million people, representing a sizeable 6.7% of total employment in the EU. With 2.7 million people working in vehicle manufacturing across 226 factories in the EU, the automotive industry accounts for 8.5% of total manufacturing jobs.

In view of the new policies aiming at carbon neutrality by 2050, progressive substitution of current fossil fuels with renewable fuel seems a highly probable scenario. Combustion engines fueled by fossil fuels or exclusively hydrogen could coexist in the near future, along with engines fueled by mixtures of fossil fuel and hydrogen [4]. This will promote the progressive decarbonization of the transport sector while maintaining a historically fundamental industry and economic activity in most developed countries.

The use of hydrogen in reciprocating internal combustion engines is not new of course. Almost all important world car manufacturers developed hydrogen-fueled vehicles and some companies, such as BMW, Ford and Mazda, are also developing cars and buses powered by hydrogen-fueled internal combustion engines (H2ICEs). In addition to automobile manufacturers, universities and research centers have contributed to the study of these H2ICEs [5–8]. In this regard, our

* Corresponding authors.
E-mail addresses: marana@unavarra.es (M. Arana), lgandia@unavarra.es (L.M. Gandía).

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Nomenclature

ANOVA	Analysis of Variance
CB	Critical Bands
f	Frequency of modulation in Equation (3).
ǵ(z)	Specific loudness weighting function in Equation (2)
H2ICEs	Hydrogen-fueled Internal Combustion Engines
ICEs	Internal Combustion Engines
JND	Just-noticeable difference
k	Calibration factor in Equation (3)
L	Loudness (sone)
L_{ZT}	Equivalent sound level (db)
L_{AT}	Equivalent sound level as measured using the A-weighting filter network (dbA)
Ĺ(z)	Specific loudness (sone/Bark)
MBP	Maximum Brake Power (kW)
MBT	Maximum Brake Torque (N·m)
R	Roughness (asper)
S	Sharpness (acum)
z	CB number (sone/Bark)

research group adapted a Volkswagen (VW) Polo 1.4 originally powered by gasoline for bi-fuel hydrogen-gasoline operation (the driver chooses whether the engine burns gasoline or hydrogen) [9]. Another study analyzed the propensity to suffer from abnormal combustion phenomena of this type of engine when fueled with hydrogen. These phenomena were characterized using several techniques, including acoustic measurements [10].

Along with gas emissions, noise is also considered an important factor in urban pollution. The population is increasingly sensitive to noise generated by road traffic in cities. Noise pollution caused by road traffic has been extensively investigated. The harmful effects of noise pollution are undeniable, both at an individual physiological level [11] and at a community social level [12–13]. The auditory and non-auditory effects of noise on health have been reviewed by Basner at al. [14]. Among the non-auditory effects, there is growing evidence that noise leads to annoyance, disturbs sleep and causes daytime sleepiness, and increases the occurrence of hypertension and cardiovascular disease. It is also worth mentioning that internal noise affects the driver's taking-risks behavior in aspects such as car-following distances and the length of gap in traffic [15] as well as speed choice [16]. All this evidence leads to increasingly restrictive regulations on noise emissions from individual vehicles [17–18] and from traffic infrastructures [19]. It is likely that the effects of these regulations are already being felt in terms of a slight decrease in noise pollution in our cities [20].

The objective of this study is to analyze the possible influence of the type of fuel (gasoline or hydrogen) on the sound levels produced by a vehicle with an internal combustion engine. Given both the high number of noise sources in a vehicle and the acoustic indices that may be related to annoyance, it is convenient to limit and specify such variables. Due to the importance of noise generation from the point of view of the public acceptance of a technology, in addition to the most standard indices characterizing sound levels, psychoacoustic indices have been measured and analyzed as well to determine the acoustic quality of the sound. When operating a vehicle at high speeds–intercity routes–the main sources of noise are aerodynamic and rolling noise. On the contrary, when the vehicle is operating at low speeds–urban routes–engine noise and noise due to structure vibration prevail over other sources. The main components of engine noise are combustion and noise associated with the intake and exhaust. We have focused this study on noise associated with combustion since the main objective is to analyze the influence of the type of fuel on the noise produced by ICEs. Therefore, the experimental setup was designed with the purpose of avoiding noise sources not being related to the effect of the fuel itself, such as aerodynamic and rolling noises, as well as noises induced by the state of the asphalt.

Tests were carried out with the aforementioned VW Polo 1.4 vehicle when stationary to eliminate rolling and aerodynamic noise. Sound pressure measurements were carried out both inside and outside the vehicle. The greatest influence on sound perception inside a conventional car is produced by the engine [21]. Previous studies have shown that engine sound induces different perceptual responses in people according to the different states of the motor: idling, constant speed or acceleration [22]. Both acoustic and psychoacoustic indices were analyzed at vehicle conditions and engine speeds that were roughly the same, except for the type of fuel (gasoline or hydrogen).

2. Experimental setup and engine characteristics

A VW 4-cylinder 1.4 L engine was used. When fueled with gasoline, it gave maximum brake power (MBP) and maximum brake torque (MBT) of 59 kW at 5000 rpm and 132 N·m at 3800 rpm, respectively. Performance was significantly reduced (MBP of 32 kW at 5000 rpm and MBT of 63 N·m at 3800 rpm) when the engine was adapted to run on H_2, mainly due to the conservative operating conditions (fuel lean operation) adopted to avoid abnormal combustion issues. These aspects have been described in detail in previous papers [5–7,9–10].

Fig. 1 shows the hydrogen feeding line fitted in the vehicle. The line connecting the gas cylinders with the accumulator requires the hydrogen pressure to be maintained at 9 bar. This is done by an initial pressure regulator placed in the car trunk. Because the operating pressure of the hydrogen injectors must be reduced to 3 bar, a second pressure regulator is required at the accumulator inlet. Two QRAE Plus PGM-2020 hydrogen sensors were used for safety purposes: one in the car trunk and the other inside the vehicle. Under normal driving conditions, no significant hydrogen leaks were detected and no hazardous situations were identified. The vehicle was lifted using a scissor lift and the tests were performed by turning the wheels freely. The following engine speeds were considered: idling, 2000, 3000 and 4000 rpm, which were measured at 0.1 s periods with 1 rpm accuracy, trying to keep them constant. The engine temperature during the tests was practically identical except at idling speed, in which case the temperature with hydrogen was around 6 °C higher than with gasoline.

As shown in Fig. 2, inside the vehicle there were an acoustic head with two microphone channels (one in each ear) in the co-driver position, and an omnidirectional microphone located in between the two front seats. An operator stood in front of the vehicle with two microphones, one in each ear. The microphones (CS-10EM Roland, electret type, omnidirectional, with response throughout the audio area and sensitivity of −40 dB ref. 1 V/Pa at 1 kHz) were connected to an H4nPro recorder, a Handy Recorder made by the ZOOM Corporation. A GRAS 40AC omnidirectional microphone was also used. They were positioned in front of the vehicle, 1.5 m away. All sensor positions were the same irrespective of whether the vehicle was fueled with gasoline or hydrogen. All the tests were carried out in a very large laboratory with no special acoustic characteristics. The study focused on the differences between the two emissions, rather than on absolute values.

Three letters were used to refer to the recordings according to the following code. The first letter refers to the type of fuel: G, for gasoline and H, for hydrogen. The second one refers to the recording device: I for the interior GRAS microphone (car inside), O for the exterior GRAS microphone (car outside), H for the interior acoustic head, and Z for the exterior acoustic head. The third letter identifies the channel (acoustic head cases): L for the left channel and R for the right channel. For example, for the experiments performed with the gasoline-fueled vehicle:

- GI: gasoline, interior microphone GRAS
- GO: gasoline, exterior microphone GRAS
- GHL: gasoline, interior acoustic head, left channel

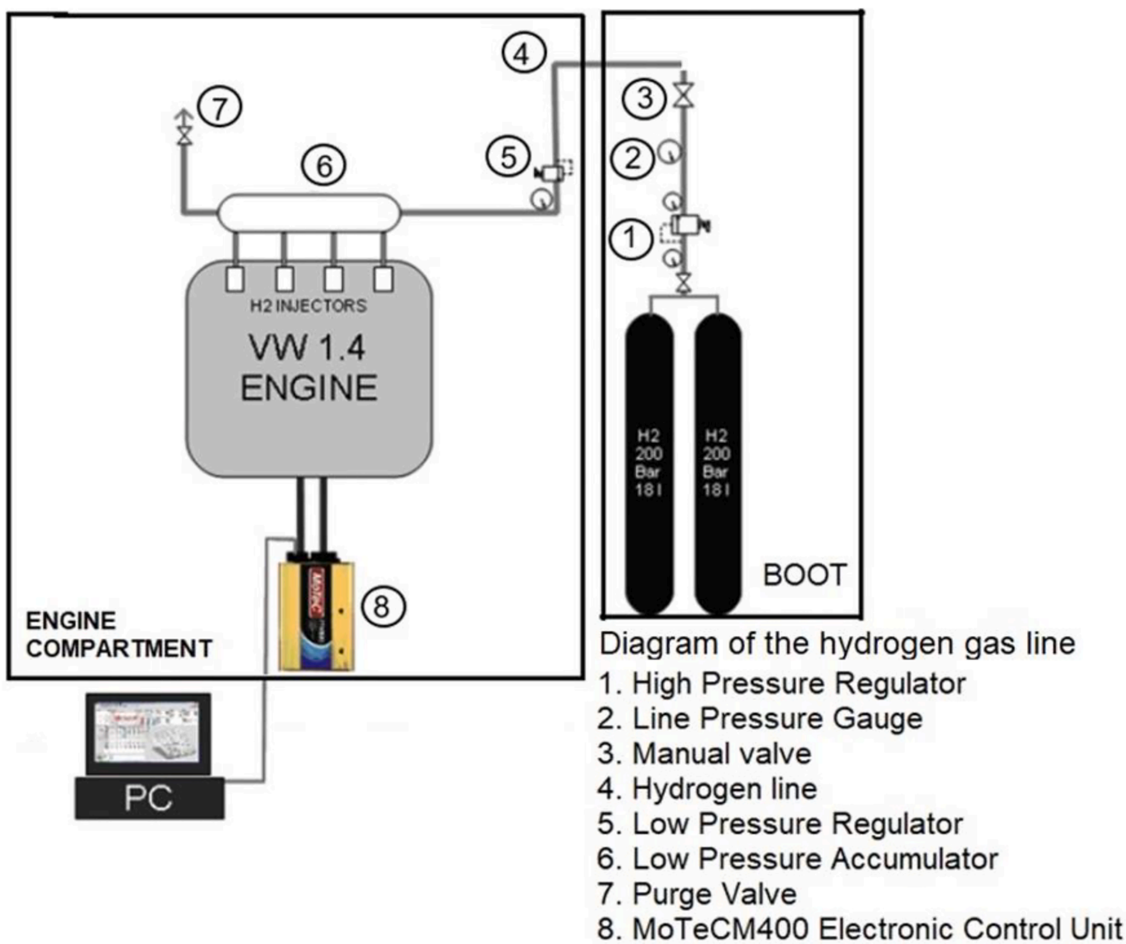

Fig. 1. Diagram of the hydrogen gas line assembled in the vehicle.

Fig. 2. Experimental setup inside the vehicle.

- GHR: gasoline, interior acoustic head, right channel
- GZL: gasoline, exterior acoustic head, left channel
- GZR: gasoline, exterior acoustic head, right channel

Changing the first letter (H instead of G) gives the same cases, but with the car being fueled with hydrogen.

An acoustic calibration signal (94 dB) was recorded on each of the 6 channels. Recordings were analyzed using the BK Connect software, both to evaluate acoustic sound levels and spectra, and to obtain psychoacoustic parameters (loudness, sharpness, roughness and fluctuation strength). The sound level analysis included: spectral power in octaves and in 1/3 octaves from 20 Hz to 10 kHz, as well as L_{ZT} (equivalent sound level, no-weighted) and L_{AT} (equivalent sound level, A-weighted) levels every 0.1 s. A stable period of 20 s of each operating speed was selected, recording the data every 0.1 s.

3. Results and discussion

3.1. Noise levels inside the car

Fig. 3 shows the sound levels (L_{AT}) generated at the omnidirectional interior microphone (I) for different engine speeds with the two fuels. Regarding noise levels, they are slightly higher with hydrogen at idling conditions, but the engine speed is also higher with this fuel. It should be noted that, in order to achieve stable idling conditions, a greater air intake is required when using hydrogen, which implies a higher engine speed compared to idling with gasoline as can be seen in the Figure. This was accomplished through a higher opening of the throttle valve at idling conditions when using hydrogen compared with gasoline. At higher engine speeds, L_{AT} obviously increases with the speed, reaching similar values for both fuels at the rest of the engine speeds (2000, 3000 and 4000 rpm).

Fig. 4 and Fig. 5 show the sound levels at the left and right channels, respectively, of the interior acoustic head.

As for the omnidirectional microphone, when idling, noise levels at the channels of the acoustic head inside the car are higher with hydrogen than with gasoline. However, no clear differences between gasoline and hydrogen are observed at higher engine speeds. In some instances, noise level is higher with gasoline while in others it is higher with hydrogen. In any case, the differences are small and not significant as judged from the results of the correlation and significance tests performed whose scatter diagram is shown in Fig. 6.

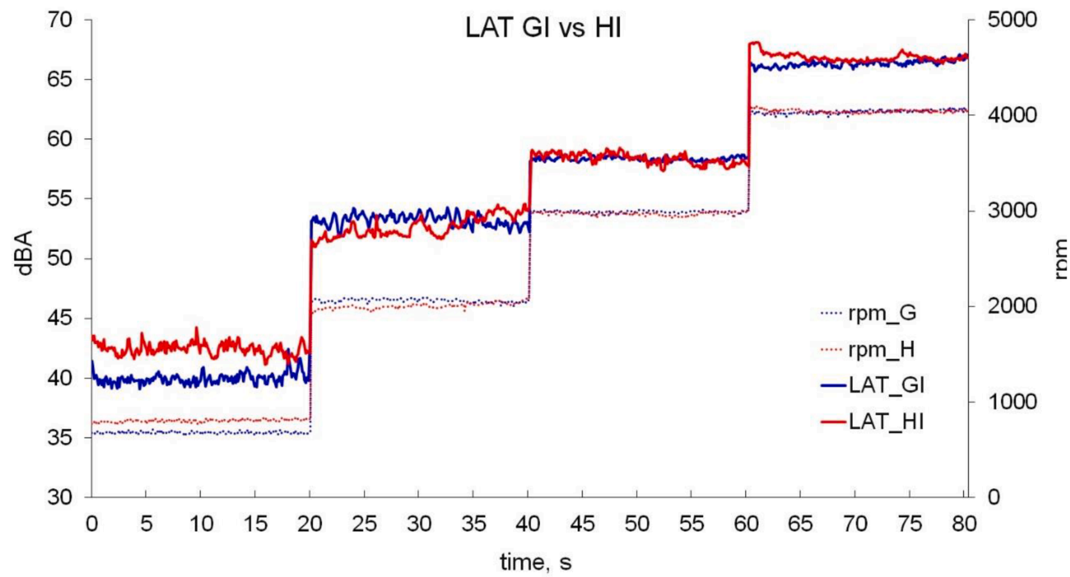

Fig. 3. Sound levels (L_{AT}) inside (I) the car for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

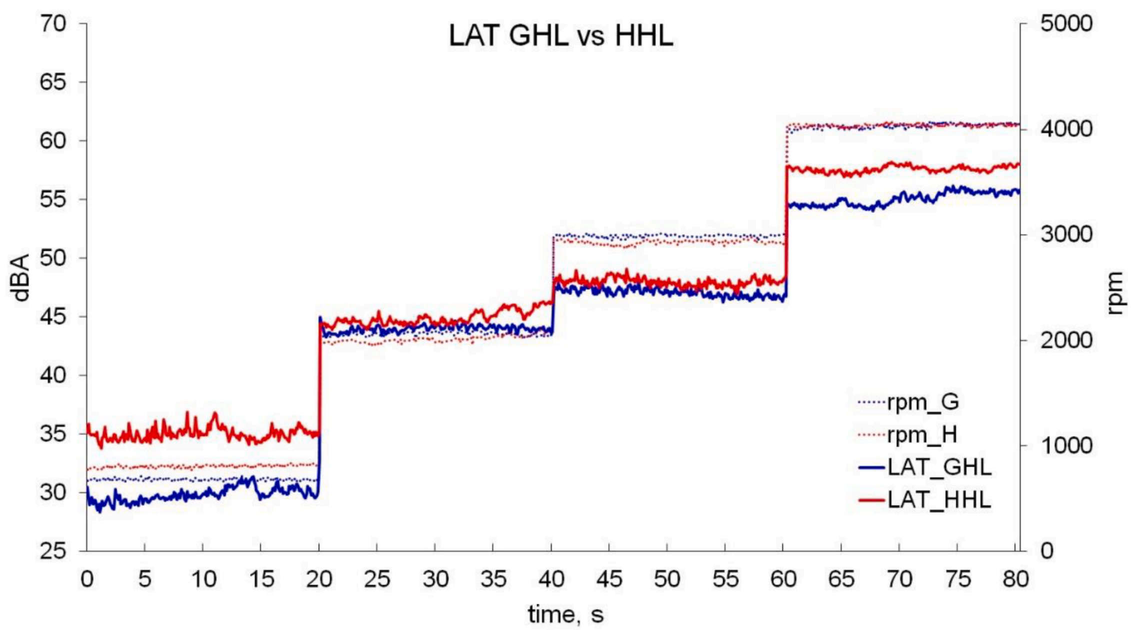

Fig. 4. Sound levels (L_{AT}) at the left channel (L) of the internal acoustic head (H) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H).

3.2. Noise levels outside the car

Fig. 7 shows the sound levels (L_{AT}) recorded by the omnidirectional outdoor microphone (O). A slight increase of noise is noticed at all conditions tested when the engine is fueled with hydrogen in spite of the engine speed being slightly higher with gasoline, except for idling conditions as explained before. Actually, the highest difference is observed precisely at idling conditions. The question arises whether these differences are, or not, significant; therefore, analysis and significance tests were carried out. Raw data have been plotted on scatter plots in Fig. 8 to induce regression lines.

An analysis of variance (ANOVA) was carried out to test the null hypothesis of no difference in the mean noise produced by each type of fuel. Two factors were taken into account: the first one is the outside noise level for each type of fuel (LG and LH; noise levels with gasoline and hydrogen, respectively). The second factor is the engine speed: R1 (idling), R2 (2000 rpm), R3 (3000 rpm), and R4 (4000 rpm). This is a balanced analysis since the sample size is the same in all cases (n_i = 200). Calculations were performed with Minitab® 19.1 (64-bit) software [23]. Table 1 summarizes the main results of the ANOVA. As can be seen, the influence of the type of fuel on the outside sound levels is fully significant ($p < 0.001$). The same conclusion is obtained both for the engine speed (as expected) and for the interaction between both factors ($R^2 = 0.9988$).

Fig. 9 shows the residual plots for the outside noise levels evidencing that the hypothesis of normality of the data is fulfilled. Differences in the means (which have a reduced standard deviation) are very significant ($p < 0.01$). Therefore, it can be concluded that the outside noise generated by fueling the vehicle with hydrogen is slightly higher than the noise generated when fueling it with gasoline. The differences are statistically significant and can be stablished between 1.1 dBA and 1.7 dBA depending on the engine speed (above idling).

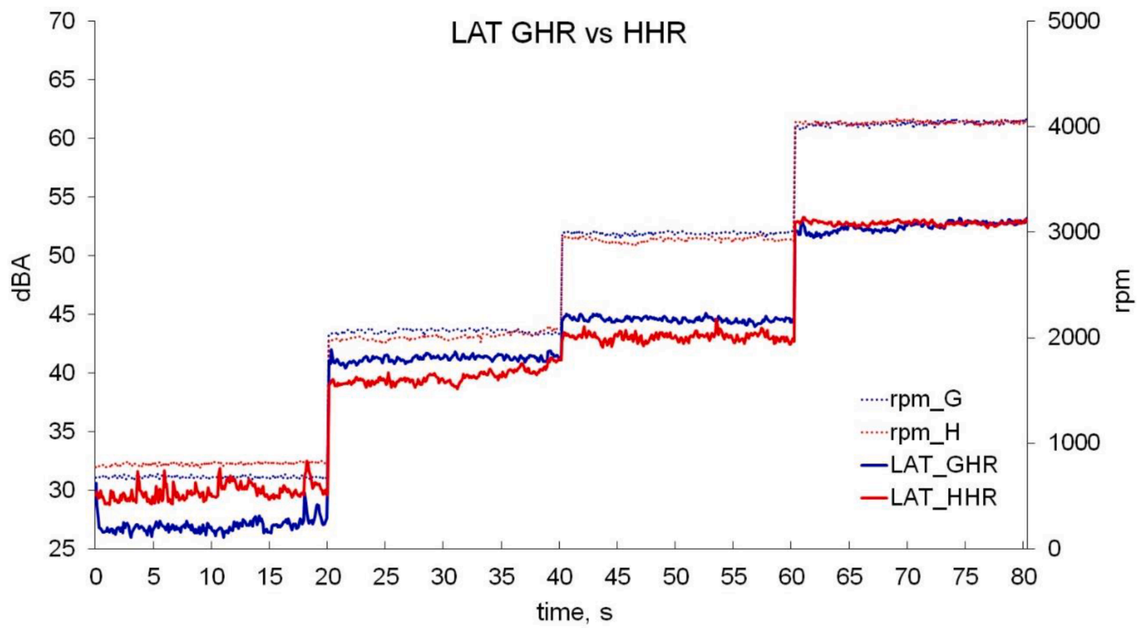

Fig. 5. Sound levels (L_{AT}) at the right channel (R) of the internal acoustic head (H) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H).

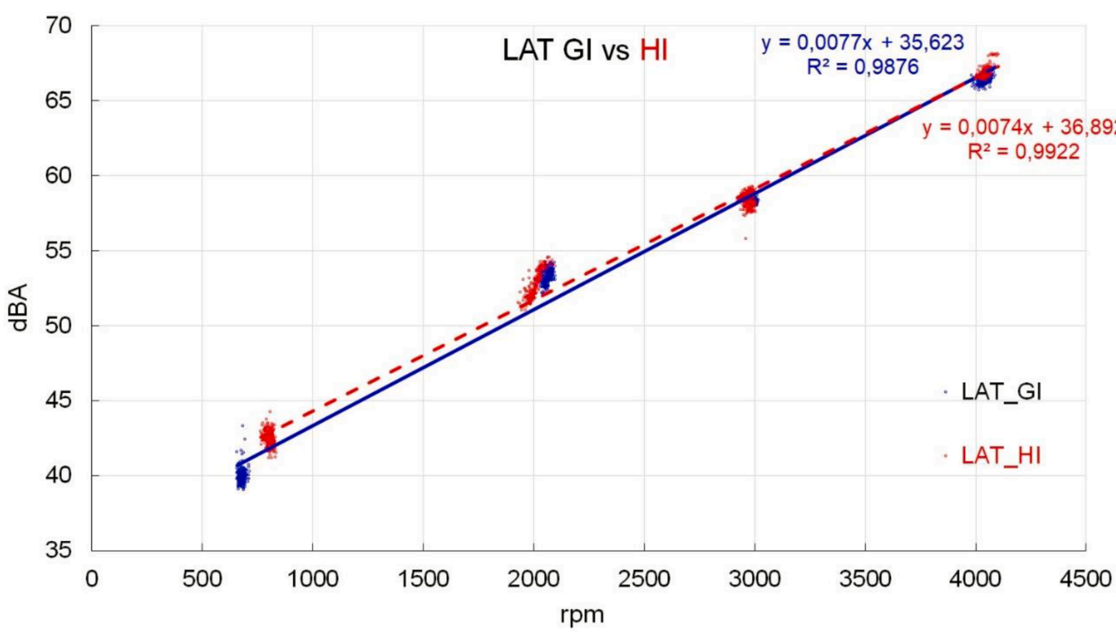

Fig. 6. Scatter plot of inside sound levels (micro omni) for different engine speeds (rpm) when using gasoline (G; blue symbols) and hydrogen (H; red symbols) as fuels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 10 shows the analysis of the outside sound (omni microphone) by frequencies (octave bands of 250, 500 and 1000 Hz). A large increase of the 500 Hz band at speeds of 3000 rpm (period within 40–60 s) and 4000 rpm (period above 60 s) is recorded when the vehicle is fueled with hydrogen. Therefore, this band is the main responsible for the increased outside noise produced when using hydrogen as fuel compared to gasoline.

3.3. Psychoacoustic parameters

Psychoacoustic parameters such as loudness, sharpness, roughness and fluctuation strength were also assessed in this study. The analysis was carried out using BK Connect software with the data recorded during 10 s periods.

The psychoacoustical Bark scale was proposed by E. Zwicker in 1961 [24] who introduced the Bark unit, in memory of H. Barkhausen, the creator of the unit of loudness level. According to the Zwicker's annoyance model [25], psycho-acoustic metrics are an alternative to express people's feelings by subjective measures rather than objective metrics based on acoustic energy, such as L_{AT}, also denoted as $L_{Aeq,T}$. Zwicker's theory describes sound processing by the human hearing system based on quantitative relations between sound stimuli and auditory perception in terms of hearing sensations. The model is based on the anatomy of human hearing. For complex sounds, the frequency

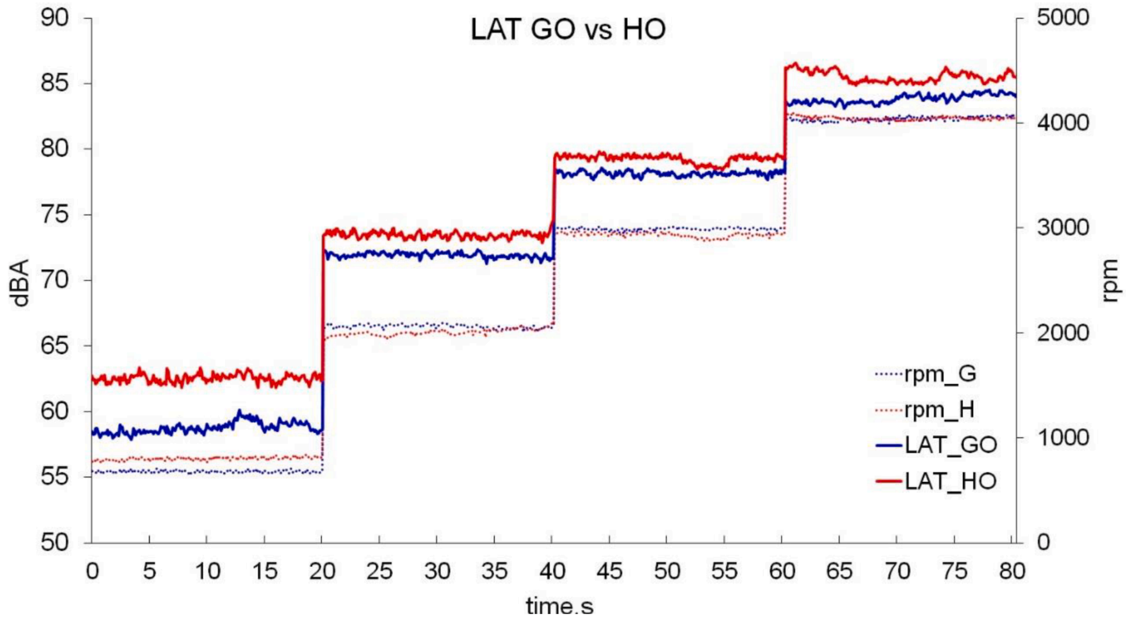

Fig. 7. Sound levels outside (O) the car for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

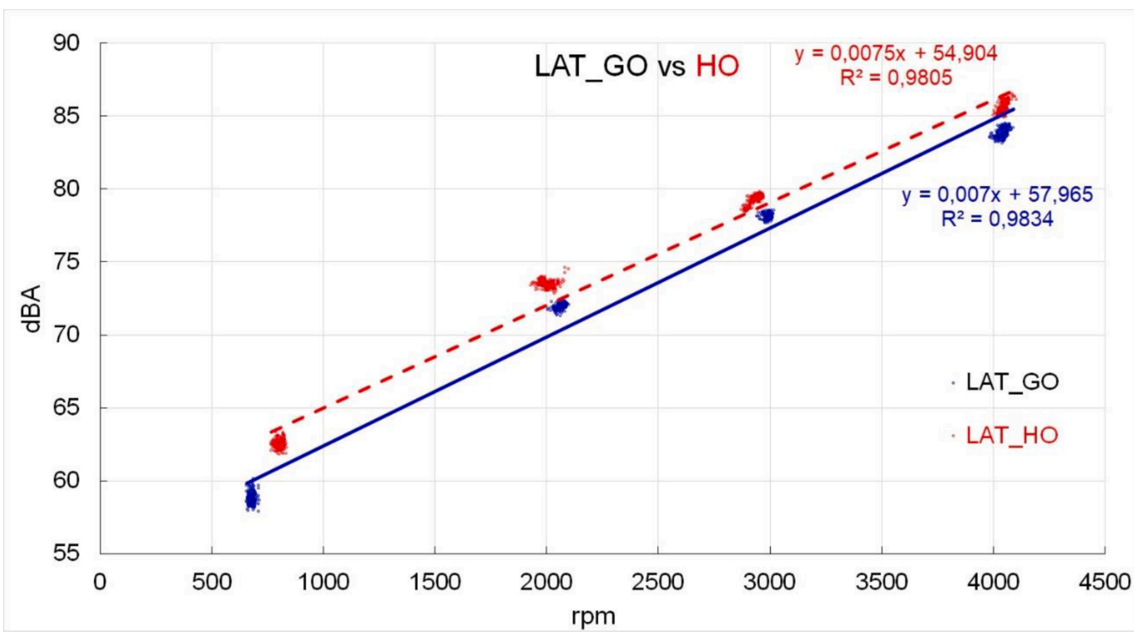

Fig. 8. Scatter plot of outside sound levels (micro omni) for different engine speeds (rpm) when using gasoline (G; blue symbols) and hydrogen (H; red symbols) as fuels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

spectrum of psycho-acoustic metrics is built in Critical Bands (CB) [26]. A critical band refers to the frequency bandwidth of the auditory filter created by the cochlea, the sensory hearing organ within the inner ear. Human hearing combines the sound stimuli, which are located very close to each other in terms of frequency, into a specific CB. When serializing these CBs, a frequency scale is created, called the CB rate scale that ranges from 1 (centered on 60 Hz with an 80 Hz bandwidth) to 24 (centered on 13.5 kHz with a 3.5 kHz bandwidth).

A brief description of the main psychoacoustic indices is given in what follows. Loudness (L) is the parameter dealing with the sound volume (intensity sensations), measured in Sones with a linear scale. It is standardized in ISO 532B. The process used to calculate L is based on the Specific Loudness (L'(z) or L contribution for each CB, where z identifies the CB number), measured in Sone/Bark. The total L is the result of the different contributions as given by Eq. (1) being Δz is the bandwidth of each Bark.

$$L = \int_0^{24\text{Bark}} L' \cdot dz \tag{1}$$

Sharpness (S) is a value of sensory human perception of unpleasantness in sounds that is caused by high frequency components. The greater the proportion of high frequencies, the 'sharper' the sound. Zwicker and Fastl [25] defined the unit of sharpness (Acum) as 'a narrow band noise one critical band wide at a center frequency of 1 kHz having a level of 60 dB'. However, sharpness is a metric that has not been standardized yet. Sharpness can be calculated according to Eq. (2) as the first

Table 1
ANOVA for the noise levels (L_{AT}) outside the car.

Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	F	P
Fuel	1	1664	1664.4	16871.81	0.000
Engine speed	3	126,332	42110.6	426858.79	0.000
Fuel × Engine speed	3	419	139.8	1416.71	0.000
Error	1592	157	0.1		
Total	1599	128,573			
Model summary					
	S	R-sq	R-sq(adj)		
	0.314090	0.9988	0.9988		
Means					
	N	L_{AT} (dBA)	Engine speed (rpm)	N	L_{AT} (dBA)
L_{AT} gasoline	800	73.17	1000	400	60.66
L_{AT} hydrogen	800	75.21	2000	400	72.70
			3000	400	78.71
			4000	400	84.68

moment of the specific loudness (L′) weighted by a function g′(z) that grows rapidly above 2.5 kHz.

$$S = 0.11\cdot\frac{\int_0^{24Bark} L'\cdot g'(z)\cdot z\cdot dz}{\int_0^{24Bark} L'\cdot dz} \quad (2)$$

There are several methods, that use different weighting functions, proposed to calculate the metric [25,27–28]. In this work, DIN 45692 method was used that is based on the Zwicker & Fastl's method [25].

Roughness (R) is a value of sensory human perception which quantifies the subjective perception of rapid (from 15 to 300 Hz) amplitude modulation of a sound. Its unit is the Asper that is defined as the roughness produced by a 1 kHz tone of 60 dB which is 100% amplitude modulated at 70 Hz. It has been found that 70 Hz modulation frequency produces the highest roughness for tones above 1 kHz. For tones below 1 kHz, the roughness increases as the modulation frequency decreases. Roughness has also been used to partially quantify sound quality in car engine noise [29].

An amplitude modulated tone can be assimilated to a sound with a rapidly changing loudness level. For sounds that last longer than 0.3 s, its objective measurement and subjective perception are the same. However, new subjective effects come into play as sound duration becomes shorter. For short-duration sounds (e.g. 10 ms), subjective perception doubles this duration (20 ms), which is important for rough sounds. This means that the perceived masking depth is smaller than the objectively measured modulation depth. Consequently, the roughness of a sound can be evaluated from Eq. (3):

$$R = k\cdot\int_0^{24Bark} f_{mod}\cdot\Delta L\cdot dz \quad (3)$$

where k is a calibration factor, f_{mod} is the frequency of modulation and ΔL is the perceived masking depth. By using a specific loudness measurement taken every 2 ms, a value for ΔL can be calculated [30]. Jeong's method [31] is another proposed method of calculation. According to the Zwicker and Fastl method [25] used here k = 0.0003 and ΔL = 20·log10[N(1)/N(99)], where N(1) and N(99) are the percentile (1 and 99) loudness values within each analysis bandwidth (1, 1/2, 1/8 bark; in this case, ½ bark).

Fluctuation Strength (FS) is similar to roughness but quantifying subjective perception of slower (up to 20 Hz) amplitude modulation of a sound. There seems to be a much higher correlation of perceived discomfort in mechanical and traffic noise with roughness than with fluctuation strength [32], so results obtained for this parameter will not be shown.

Figs. 11–13 show the results for loudness, sharpness and roughness, respectively, obtained inside the vehicle with the omnidirectional microphone. In what follows the Figure legends will show the initial of

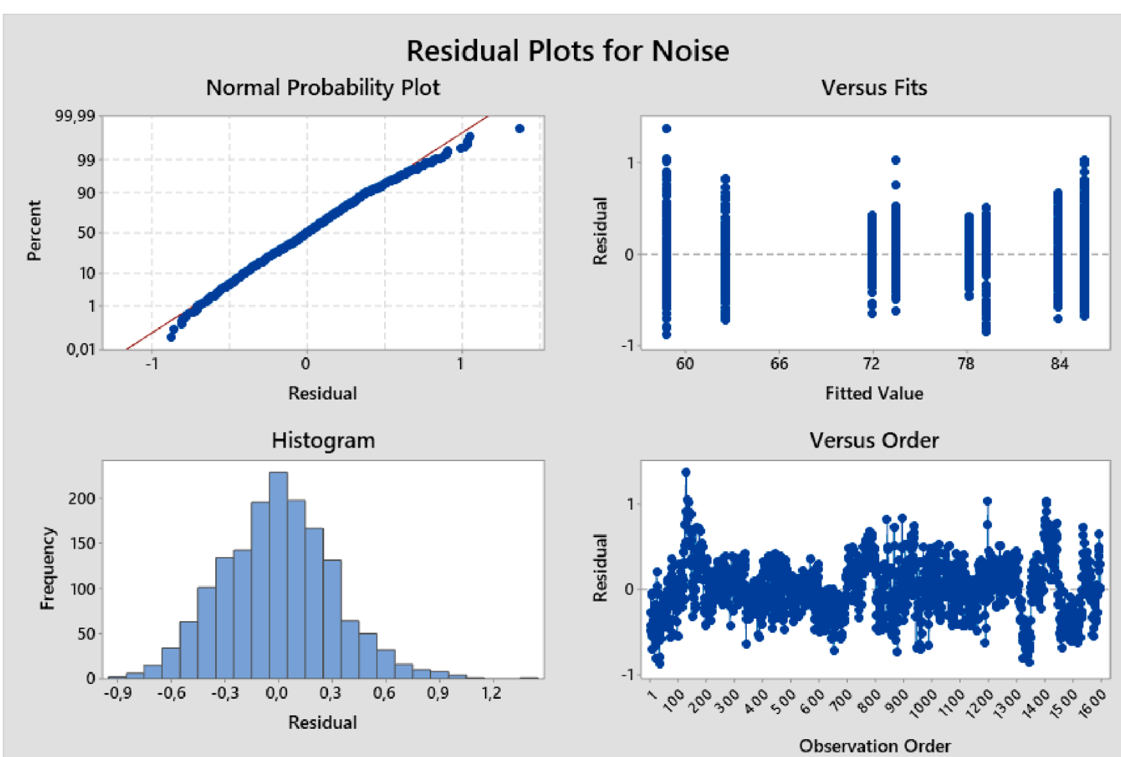

Fig. 9. Outside noise levels: residual plots for normality test.

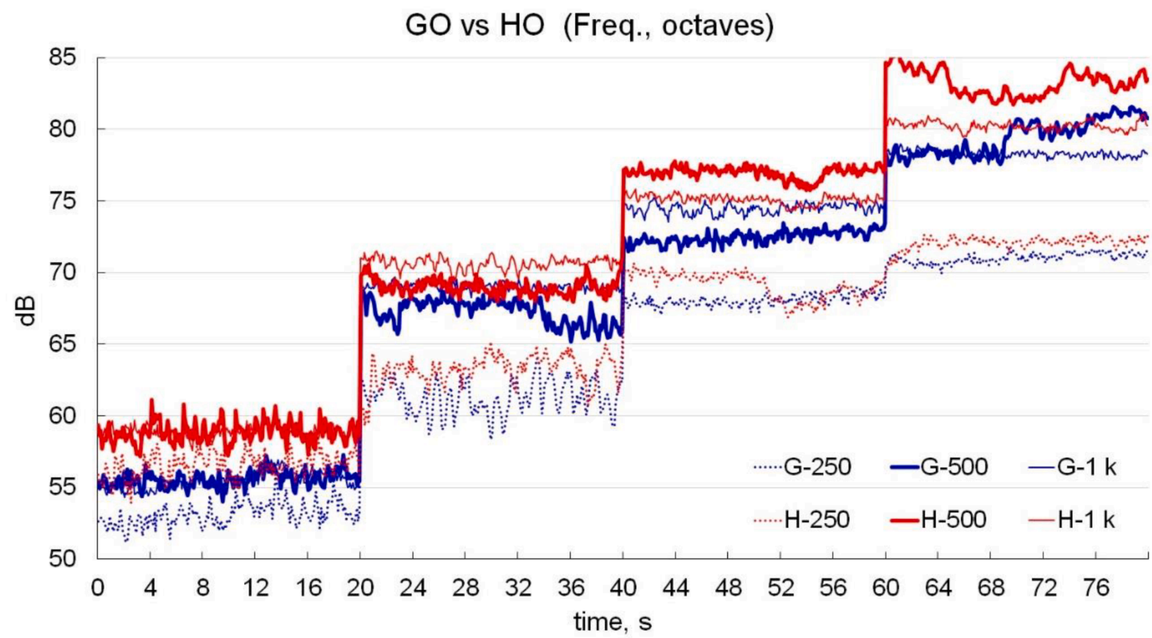

Fig. 10. Analysis in terms of octave bands at 250 Hz, 500 Hz and 1 kHz of the outside sound levels produced at different engine speeds when fueled with H_2 (red lines) and gasoline (blue lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

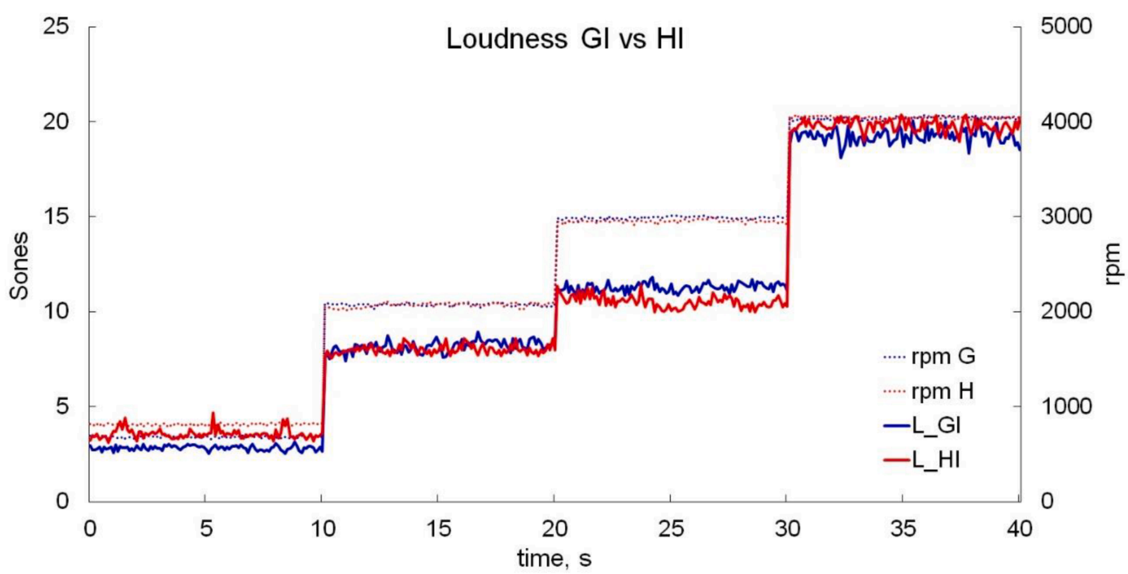

Fig. 11. Loudness inside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

the plotted parameter, e.g. Loudness_GI will be indicated by L_GI.

The scatter plot for loudness using gasoline and hydrogen is given in Fig. 14. The regression lines are practically identical; however, there are small differences in the means at 3000 and 4000 rpm. Obtaining statistically significant differences in the mean difference (mainly due to the reduced dispersion of the results) does not signify that such differences must be clearly distinguishable by the human ear. For the results obtained for the outside noise levels, L_{AT} differences were between 1.14 dBA and 1.70 dBA, except at idling (3.78 dBA). Results are expressed to two decimal places, rather out of a mathematical custom (and necessary precision) than by realistic auditory sensations. Based on human perception, not only is the second decimal unnecessary, but the first one is also doubtful. The Just Noticeable Difference (JND) of a sound signal depends on several factors, such as whether it is experienced in free-field or diffuse-field, if it is experienced with a pure tone or broadband noise, etc. Of course, it also differs among people. In experiences of acoustic perception in rooms, the JND of some parameters is usually within 1–2 dB [33,34]. Even the accuracy of a type I sound level meter is between ± 2 dB from low (25 Hz) to high (10 kHz) frequencies [35]. In conclusion, differences of $<$1 dB should not be taken as auditorily significant.

As for the psychoacoustic parameters outside the vehicle, Figs. 15–17 show the results for loudness, sharpness and roughness, respectively, obtained with the omnidirectional microphone.

A two-factor analysis of variance (ANOVA) similar to that carried out for the outside sound levels has been carried out for loudness. It is also a balanced analysis though the sample size is $n_i = 100$ (800 samples for the four speeds and the two fuels). Table 2 summarizes the results of the

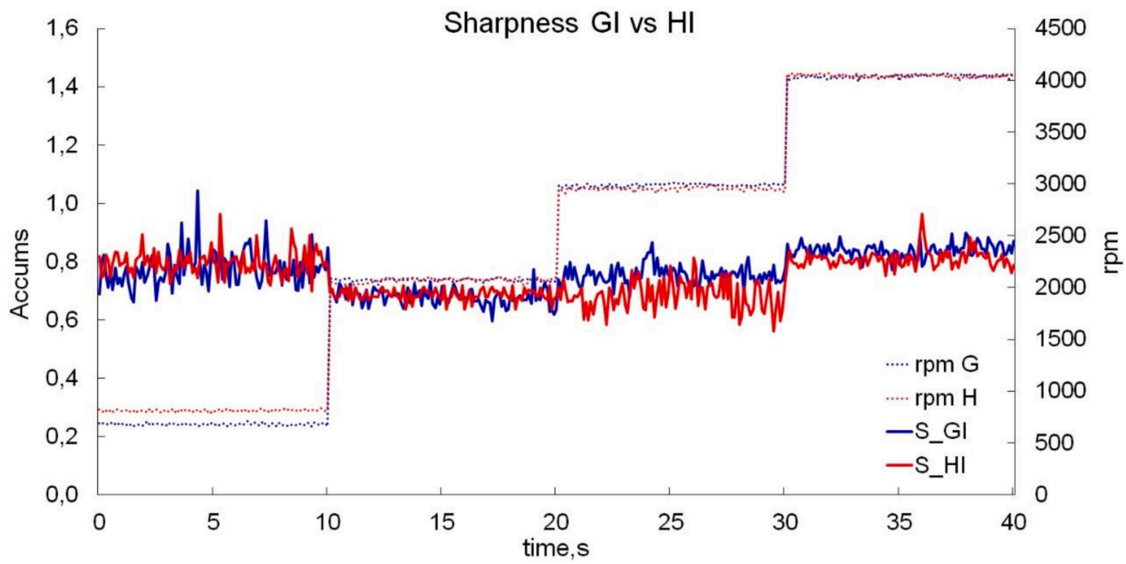

Fig. 12. Sharpness inside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

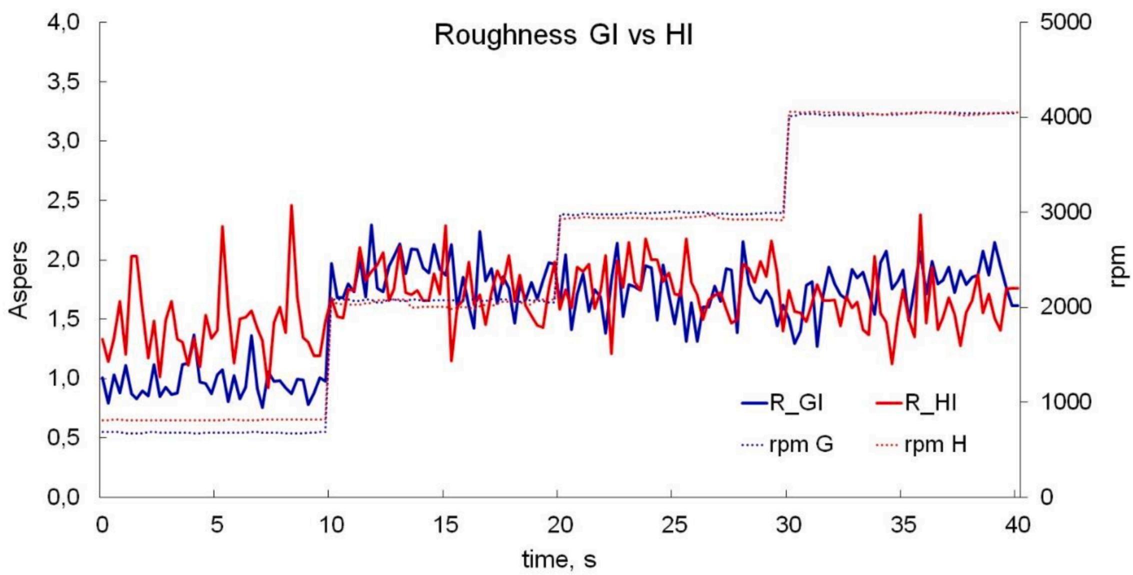

Fig. 13. Roughness inside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

ANOVA. As can be seen, the influence of the type of fuel on the outside sound levels is fully significant ($p < 0.001$). The same conclusion is obtained both for the engine speed and for the interaction between both factors. It can be seen that the difference between means is greater than the value assigned by chance with significance greater than 99%. The corresponding scatter plot is given in Fig. 18.

A test of significance (see Table 3) has also been performed to analyze the homogeneity test. As shown, the difference between means is again greater than the value assigned by chance with significance greater than 99%. Therefore, as for the sound level, loudness is higher when using hydrogen as fuel compared to gasoline.

In relation to the JND of the described psychoacoustic parameters, some works report on slightly different results depending on the type of noise used in the audio tests. For example, for earthmoving machine noise, the JND in loudness was found around 0.8 sones and the corresponding figure for sharpness was found around 0.04 accums [36] even though the JND in loudness becomes greater as the sound pressure level of the signal increases. For refrigerator appliance noise, JND obtained for loudness and sharpness was about 0.5 sones and 0.08 accums, respectively [37]. Being a little more conservative and assuming JND for most of the population (above 90% instead of 75%), it can be assumed that JND of 1 sone and 0.08 accums are more reliable values. Regarding roughness, most papers on the just-noticeable roughness differences had been carried out with amplitude-modulated pure tones with a varying degree of modulation. The JND in roughness is estimated to be about 17% [38]. However, this parameter seems to be dependent on the sound level.

In summary, the homogeneity tests for loudness do not show significant differences in the measurements taken inside the vehicle. On the contrary, they turn out to be greater outside (between 2 and 4 sones) when the fuel is hydrogen. Regarding sharpness, the homogeneity test shows differences between the means with a value equal to or less than the JND of the parameter (0.08), so they are not considered significant; this applies for both input and output noise levels. This can be explained taking into account that sharpness is calculated according to Eq. (2) as the first moment of the specific loudness (L') weighted by a function $g'(z)$

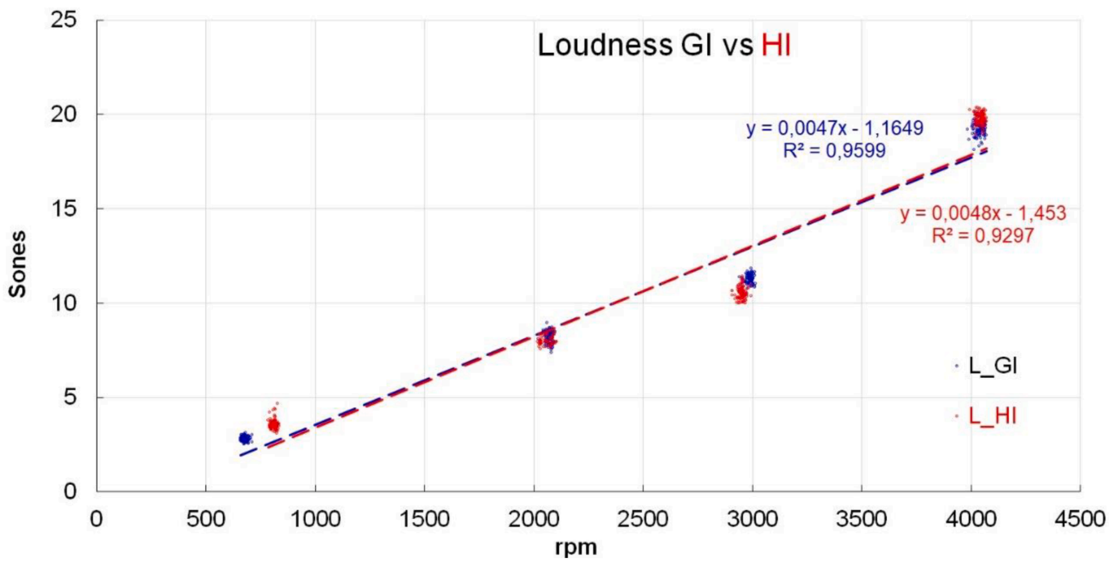

Fig. 14. Scatter plot of inside loudness (micro omni) for different engine speeds (rpm) when using gasoline (G; blue symbols) and hydrogen (H; red symbols) as fuels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

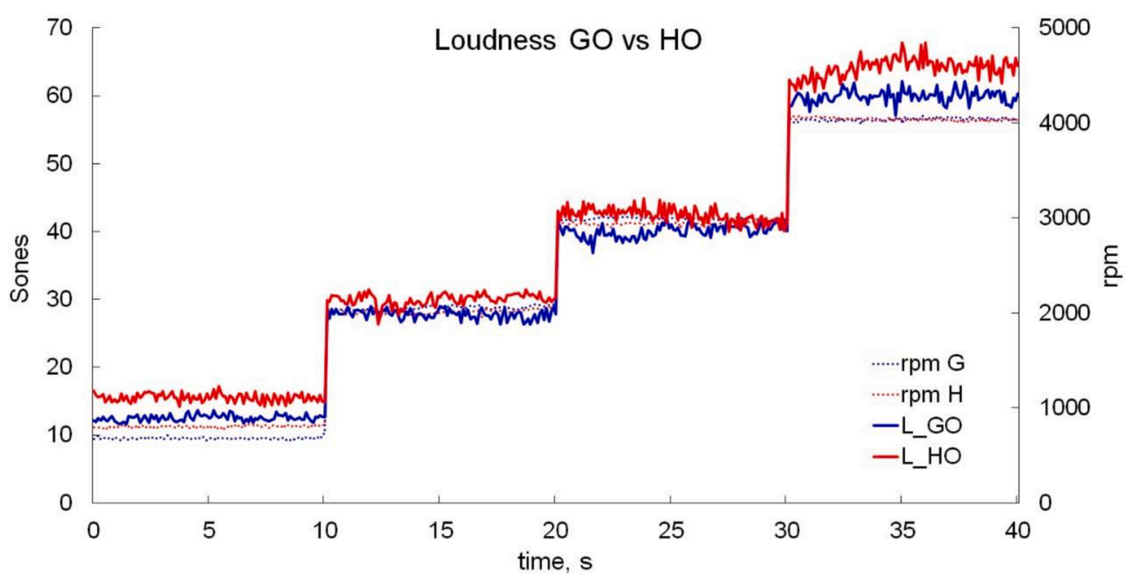

Fig. 15. Loudness outside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

that grows rapidly above 2.5 kHz. However, differences in the spectral levels of the noises produced by the two fuels are more pronounced at low frequencies (see Fig. 10), being negligible at high frequencies. As for roughness, the conclusions are similar; its value is determined by the variations (from 15 to 300 Hz) in the amplitude modulation of the sound. In view of the results obtained, there are not significant differences among the roughness produced for both fuels. However, for inside levels at idling speed (Fig. 13), there is a notable difference in the roughness value, which is significant. In this case, the sound levels are very low and the influence on the value of this parameter is more noticeable.

According to Heywood [39], noise may be generated in vehicles by aerodynamic effects as well as by forces resulting from the combustion process or from mechanical excitation by rotating or reciprocating engine components. In this work, the origin of noise differences should be mainly due to be the combustion process because the tests were performed with the same engine for both fuels and with the vehicle stopped. As for combustion noise, it is due to the in-cylinder pressure gradient generated during combustion and there are also mechanical contributions associated to the driven valve system and auxiliary equipment [40]. Noise produced by the sharp increase of in-cylinder pressure is strongly affected by the heat release rate and fuel burning velocity, which in turn mainly depend on the fuel properties, injection strategies and fuel–air mixture composition [41–46]. In a recent paper by Soloiu et al. a literature review is presented on the many factors affecting noise and vibration in ICEs [47]. In this nice reactivity controlled compression ignition study, authors emphasize the strong influence of the chemical properties of the fuel on those phenomena. As a result, fuels or fuel blends that are more reactive, thus leading to higher heat release rates and combustion pressure gradients, are also louder [47]. On the other hand, Torregrosa et al. also found an important influence of the oxygen concentration in the intake on the noise

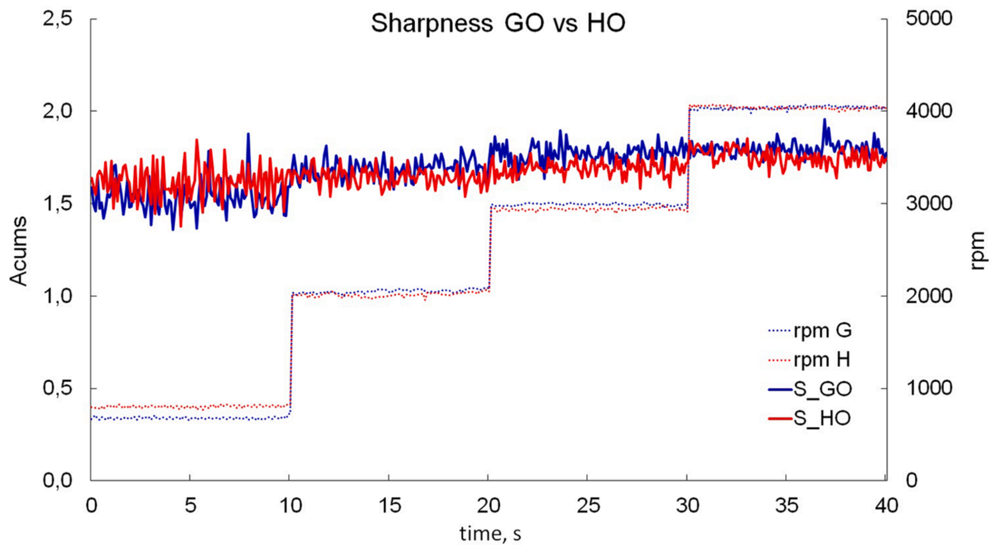

Fig. 16. Sharpness outside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

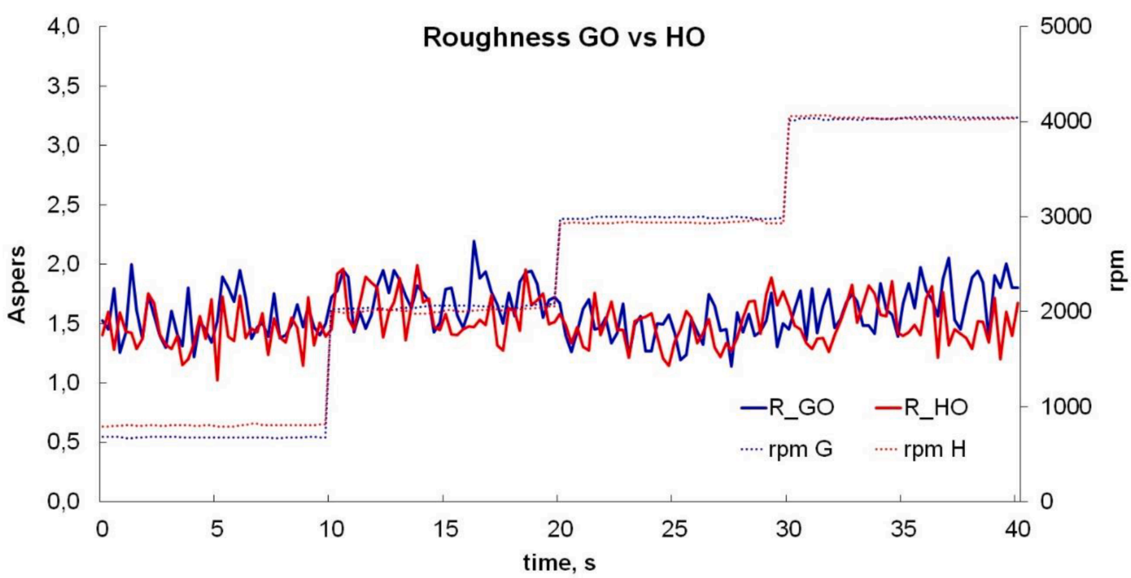

Fig. 17. Roughness outside the car (micro omni) for different engine speeds (rpm) when using gasoline (G) and hydrogen (H) as fuels.

Table 2
ANOVA for the loudness levels inside the car.

Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean squares (MS)	F	P
Fuel	1	1721	1721.3	1948.46	0.000
Engine speed	1	247,340	82446.8	93327.31	0.000
Fuel × Engine speed	3	129	43.0	48.67	0.000
Error	3	700	0.9		
Total	792	249,890			
Model summary					
	S	R-sq	R-sq(adj)		
	0.93990	0.9972	0.9972		
Means					
	N	Loudness (sones)	Engine speed (rpm)	N	Loudness (sones)
Loudness gasoline	400	35.08	1000	200	14.03
Loudness hydrogen	400	38.02	2000	200	28.90
			3000	200	41.24
			4000	200	62.02

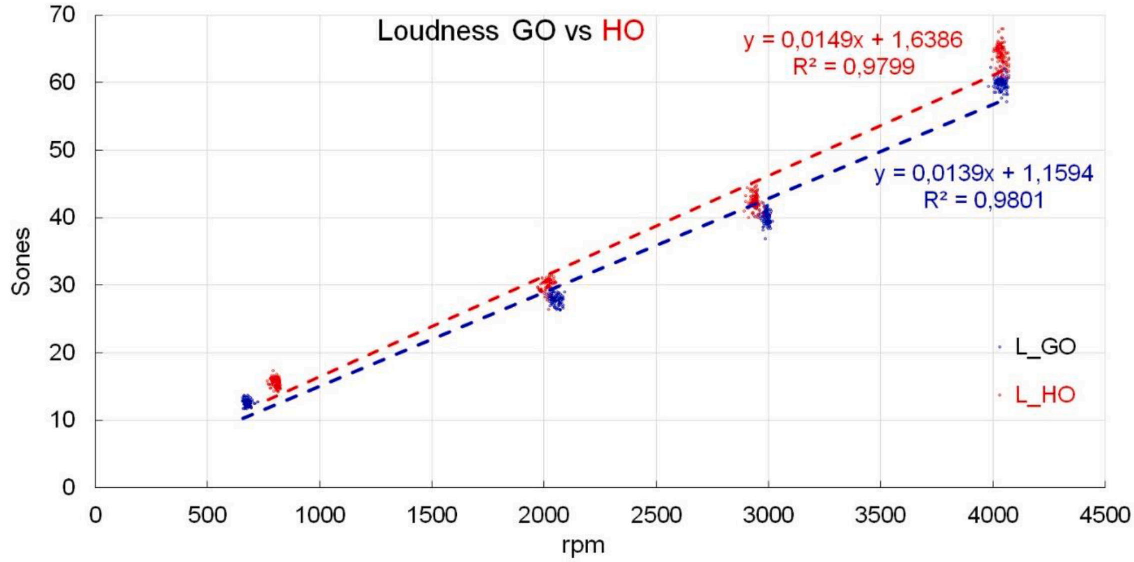

Fig. 18. Scatter plot of outside loudness (micro omni) for different engine speeds (rpm) when using gasoline (G; blue symbols) and hydrogen (H; red symbols) as fuels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Homogeneity test for outside loudness (values given in sones).

	Gasoline			Hydrogen					$p < 0.01$
Engine speed (rpm)	n_1	m_1	σ_1	n_2	m_2	σ_2	m_2-m_1	σ_d	$2.6\cdot\sigma_d$
Idling	100	12.52	0.47	100	15.54	0.63	3.02	0.08	0.20
2000	100	27.82	0.69	100	29.98	0.85	2.15	0.11	0.29
3000	100	40.07	0.95	100	42.42	1.10	2.35	0.15	0.38
4000	100	59.92	0.96	100	64.13	1.49	4.21	0.18	0.46

combustion generated by a compression-ignition engine fed with gasoline/diesel blends [48]. In this regard, low oxygen concentrations lower the fuel burning velocity thus reducing both the rate of pressure change and the intensity of the resonance in the combustion chamber.

As for the results found in this work, both reactivity, as given for example for the combustion speed, and heat release rate are significantly higher for hydrogen than for gasoline (or isooctane) [49,50], which can explain the higher noise level and loudness recorded outside the vehicle when burning hydrogen. In addition, engine operation with hydrogen under fuel lean conditions, as in our case, implies a comparatively high concentration of oxygen in the intake, which can also contribute to higher burning velocities and increased combustion noise.

4. Conclusions

Using a commercial vehicle with an internal combustion engine adapted to run on both gasoline and hydrogen, an experimental setup has been designed and used to compare the sound levels produced when using those fuels. Both acoustic and psychoacoustic indices were analyzed at engine idling and different speeds up to 4000 rpm. The sound levels (L_{AT}) inside the vehicle were practically identical with both fuels at different operating regimes except for idling since, for it to be stable, idling with hydrogen requires greater air intake that leads to higher speed. Outside noise levels were slightly higher when the engine ran on hydrogen. Average values showed increases of 3.8 dB when idling, 1.5 dB at 2000 rpm, 1.1 dB at 3000 rpm, and 1.7 dB at 4000 rpm. Although the differences are small they are statistically significant ($p < 0.01$). A frequencies analysis evidenced that the differences were mainly due to the band of 500 Hz.

Psychoacoustic parameters have been also measured, resulting in differences between the fuels mainly at idling conditions. At higher speeds (2000 to 4000 rpm), differences in sharpness and roughness values are less than the JNDs of the parameters. The homogeneity tests for loudness parameter do not show significant differences in the measurements taken inside the vehicle. On the contrary, they turn out to be superior outside (between 2 and 4 sones) when the fuel is hydrogen.

Increased noise level and loudness of hydrogen compared to gasoline, though statistically significant, are small and do not create any annoyance issue.

Finally, it has to be highlighted that a direct monitoring of the combustion phenomena within the cylinders during the acoustic measurements could not be performed in this work. Such as study would have been helpful to better understand the differences of noise caused for hydrogen and gasoline in terms of their performance as fuels. This limitation as well as the study of the contribution of the block engine vibration to the global noise are expected to be addressed in a future work. Another interesting aspect would be to auralizate, that is, to model and simulate the sounds produced by the engine, and then perform psychoacoustic tests in the laboratory to study the perceived sound quality.

CRediT authorship contribution statement

Miguel Arana: Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft. **Ricardo San Martín:** Investigation, Data curation, Formal analysis, Writing – original draft. **José Carlos Urroz:** Investigation, Data curation, Methodology. **Pedro M. Diéguez:** Project administration, Resources, Methodology. **Luis M. Gandía:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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