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Technical note

# Noise emission from alternative fuel vehicles: Study case

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ABSTRACT

Noise pollution has become a source of social tension, with economic development on one hand and quality of life on the other. The number of vehicles on the road is increasing constantly, especially in urban areas. As a consequence, environmental pollution has also increased, not only due to fuel emissions harmful to people, but also due to noise pollution; therefore, the control of the acoustic environment has turned out to be a key issue and a technological challenge.

According to Ibarra et al. there have been recent studies on the quantification and characterization of noise emitted by vehicles in the near and far fields, but this kind of work has mainly been developed for internal combustion vehicles fuelled by diesel or petrol. With new emerging technologies aimed at improving world social and environmental conditions, new alternative fuel vehicles are appearing around the world, especially in large cities. These new vehicles have not yet been characterized regarding their noise emissions. The aim of this work is to characterize and quantify the level of noise emitted by alternative fuel vehicles, such as hybrid and electric vehicles, for both near and far fields. To achieve this, it would be very useful to incorporate simulations of noise mapping.

Experimental results of this work demonstrate that hybrid and electric engines have made important contributions towards reducing engine noise in suburban and urban traffic, at least 10 dBA less than diesel or petrol vehicles; however, noise from the tyre-ground interaction remains the main source of noise, especially in suburban roads at high speeds.

## 1. Introduction

Any study aimed at increasing comfort for humans should consider the sounds in their surroundings, and in our case, the noise generated by vehicles is one of the most important aspects of urban life, as shown by Van Mierlo et al. [1] or in a deeper analysis by Ibarra [2]. In addition, according to Parry et al. [3], climate change, economic policies and petroleum production have recently increased the desirability of vehicles with alternative sources of power, which appear to offer certain advantages in many ways compared to conventional cars. These two ideas converge on the fact that noise emission by alternative fuel vehicles, is a critical point to be analysed in the near future.

Conventional studies of these changes, such as social studies of technological systems in vehicles [4] or the challenges of integrating electrical systems in conventional systems [5] and other research are typically focused on aspects such as contamination by particulate emissions of carbon dioxide, but only a few works have researched the noise contribution in alternative energy vehicles such as hybrid and electric.

The characterization of alternative energy vehicles regarding noise emission is important due to the fast growth at local and global levels, since, eventually, efforts will focus on their analysis. It is worth noting the study by Sandberg et al. [6] where they point that electric vehicles are so quiet, that their lack of noise could pose a risk for certain groups in society, e.g. blind pedestrians and cyclists mainly. However, they analysed only the perception of the presence of a car by its noise, the distant field, but there was not enough detail regarding the methodological procedure in a real urban scenario or at least in an experimental scenario to parameterize the noise emission of these vehicles. While it may be necessary to perceive the approach of an alternative fuel vehicle, it is assumed that such a vehicle would be totally silent. However, the noise generated by the tyres has not been measured effectively e.g. [7].

Thus, in order to face the challenging goal of maintaining a pleasant acoustical environment with a continued trend towards more vehicles, new and audacious emission control measures are needed. With this aim, we validate in this work the methodology for measuring the contribution of each individual alternative fuel

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vehicle to the whole road traffic noise [8]. On-board measuring devices have been previously used for driver identification purposes [9], for measuring the quality of traffic flow [10], and for measuring the noise contribution of diesel and petrol vehicles [11–14].

## 2. General methodology

The tests are made along to the suburban an urban circuit with different drivers, and with different driving modes provided by the vehicles.

For each of these tests, the signals were recorded from each microphone through the template of the PULSE system, and we processed them to obtain the following data:

- The time evolution of the equivalent level of 1 s ($L_{eq,\ 1s}$) each of the microphones and for each of the runs, along the urban and suburban courses.
- The overall equivalent levels, $L_{eq}$, of suburban and urban courses, of engine and rolling noises for each of the driving modes.

$$\langle L_{Aeq} \rangle_T = 10\log_{10}\left[\sum_{Ti} 10^{L_{eq,T_i}/10}\right], \tag{1}$$

with $T = \sum T_i$.

- The level histograms along the runs, e.g. the time percentage that the equivalent level is in each level band.
- The noise levels estimated in the far field.

Since most regulations are based on noise levels measured at the far field, a study of the near-field to far-field sound propagation in vehicles is pertinent. Therefore, analyse the relationship between the noise measured at the near field and the noise radiated to far field. Separated filters are described then to extrapolate the two near field noise levels to the far field, where they will be added energetically. The main factors influencing these extrapolation filters are the geometrical spreading and the interaction with the ground [8].

The sound pressure level at the far field point will be

$$L_{m3}(\omega) = L_{m1}(\omega) + L_{13}(\omega) \oplus L_{m2}(\omega) + L_{23}(\omega), \tag{2}$$

where $\oplus$ stands for energetic (logarithmic) summation. The first term of this summation includes the attenuation between the engine microphone and the far field point. The second term comprises the sound pressure loss between the tyre microphone and far field point.

## 3. Study case

The system used in this work includes two acoustic sensors (electret microphones) to measure the contribution of the two main noise sources in conventional vehicles, namely, the tyre-ground interaction noise, and the engine noise. In the case of alternative vehicles tyre-ground interaction is the primary source of noise, with a smaller contribution from the engine. Fig. 1 shows the location of microphones near the noise sources of vehicles. Simultaneously, information about the driving performance can be picked up from the CAN BUS interface of the vehicle. Analysis of coincident acoustical/driving performance data in real driving conditions will allow setting some correlation, if any, between the noise emitted by individual alternative vehicles and the driving performance [15–17].

Typically, commercial vehicles with alternative fuels are classified by their source of power, mainly into hybrid or electric. For the purpose of this study, two vehicles (described below) were used. They were selected as being representative of vehicles widely found in circulation around the world, especially in big cities. These vehicles are compact, of medium capacity and with an average power of 100 kW (135 hp). According to Armero [18], the vehicles selected represent 0.05% of the world vehicles.

Since the market proportions of hybrid and electric engines in Mexico are 99% and 1%, respectively, of the total of alternative vehicles, it seems practical to analyse both types in this study. Taking also into account the vehicle recorded statistics published by AMDA [19] (Mexican Association of Vehicle Dealers), the chosen vehicles were:

- Vehicle 1: Toyota Prius Hybrid
- Vehicle 2: Nissan Leaf Electric,

Two driving courses were chosen in the Tlalpan neighbourhood, in the south of Mexico City. The suburban road, runs along the Periferico ring road, which supports a traffic density of 600,000–800,000 vehicles per day. It has a length of 7 km (5.4 mi), with three lanes in each direction, and a maximum speed limit of 80 km/h. The $L_d$ in this area, according to the above referred preliminary noise map of Mexico City, is >85 dBA.

The urban road includes streets with speed limited to 50 km/h, supporting a traffic density from 120,000 to 140,000 vehicles per day, with a $L_d$ of 75 dBA. 50% of the circuit runs through one way streets of three lanes, while the other 50% runs roughly along streets with four lanes in each direction. This urban road is approximately 8.4 km long and is equipped with 24 sets of traffic lights.

Two professional drivers were selected for testing the two vehicles. Two microphones were connected to a PULSE Labshop system to measure the engine and tyre-road interaction noise at the near field of the vehicles. Concurrent driving conditions and radiated noises were measured with the vehicles running in real conditions, e.g. sharing the urban and suburban roads described above with the normal traffic. Previously, both microphones had been adjusted with a sound level meter. Driving condition parameters were measured through the vehicles' CAN BUS system, which includes an ODB2 module [20]. This system is interfaced to the acquisition system through an ELM327 probe, allowing picking up information from three signals, namely, the engine speed, the engine load, and the vehicle speed.

### 3.1. Test procedure

Once the vehicles had been fitted with the test instruments, the drivers were asked to run both courses, suburban and urban, with each vehicle, following the current traffic conditions. The hybrid vehicle offers three driving modes (normal, eco and power) and the electric vehicle offers two driving modes (normal and eco), and all the modes were tested.

The tests were conducted at different times, morning and evening, and on different days of the week. Acoustical and driving condition measurements were synchronously triggered at some starting point of each circuit. Once the circuits were completed, the vehicles returned to the laboratory for transferring the data to the workgroup server for further post-processing and analysis.

Besides the microphones, for acoustical data, and the CAN BUS system, for driving conditions data, a GPS was used to record information of the vehicle position, speed, travelled and time, and whether the vehicle was stationary or moving.

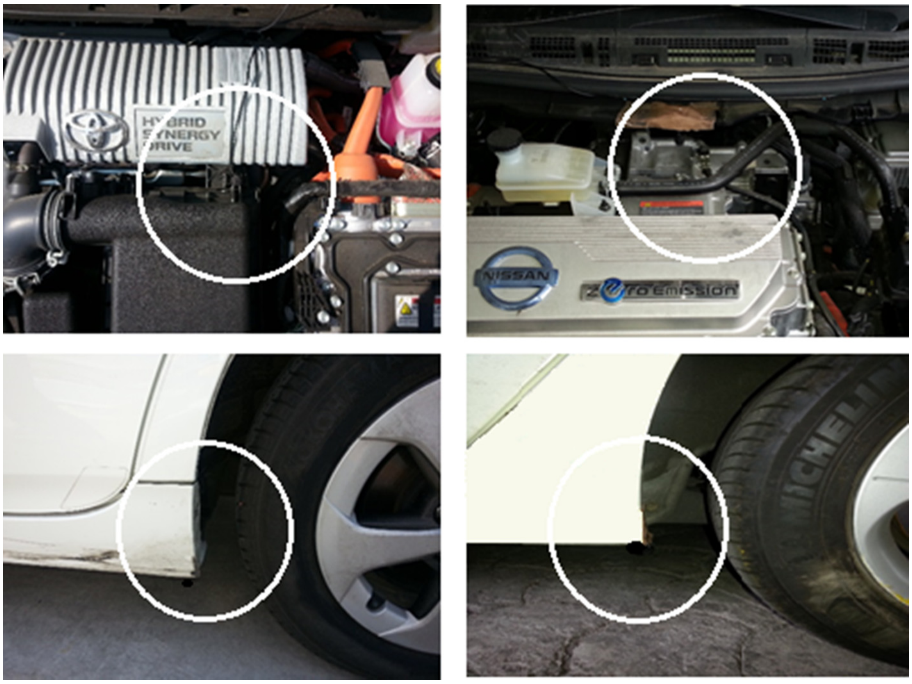

**Fig. 1.** Location of the microphones in hybrid (left) and electric (right) vehicles.

## 4. Experimental results

The two alternative vehicles (hybrid and electric) were driven by the two drivers along the urban and suburban roads in standard driving. As expected, most of the driving parameters were similar for the normal and eco driving modes for both alternative vehicles. It was noted that the hybrid vehicle, in power mode, used higher average and maximum RPM than in the others driving modes. This was due to the higher acceleration in traffic or more power needed when merging onto the highway. It increases the gas pedal response (or throttle response) to pick up the pace when it is needed [21], hence more fuel is consumed. The hybrid car spent more time stationary when set to the power driving mode than in the other driving modes. The electric car, on the other hand, spent slightly longer time stationary when running on normal driving mode than when running on eco mode.

The suburban road contains a direction changing, which is done in a U-turn without a traffic light. A noise increase from the engine of the hybrid vehicle was recorded in power driving mode, due to higher RPM, in comparison with the other driving modes. The engine noise is higher for the hybrid vehicle than for the electric vehicle, due to the characteristics of the hybrid engine.

The tyre-ground interaction noise for the hybrid and electric vehicles along the suburban is closely correlated with the vehicle speed. However, whilst the tyre-ground interaction noise in normal mode is a little higher than the eco mode for the electric vehicle, the differences are less noticeable in the case of the hybrid vehicle.

For the sake of comparison, Fig. 2 shows the level histogram of time history of all driving modes, for the engine and tyre-ground interaction noises of both hybrid and electric vehicles, along the suburban road. Since the traffic conditions were different for all the runs, the drivers adjusted their driving (e.g. changes in direction to avoid traffic jams) as necessary. These are reflected in the low levels in the respective histograms. The histograms of power mode and normal mode for the hybrid vehicle are a little displaced towards higher levels. Notice also that tyre-ground interaction noise is higher than the corresponding engine noise, in both hybrid and electric vehicles, for all driving modes. Table 1 summarizes the overall $L_{eq}$, for engine and tyre-ground interaction noises, and each driving mode of the hybrid vehicle along the suburban and urban roads. There are not significant differences between each driving mode: 2–4 dBA, and 6–9 dBA for the two types of road.

The urban road contains several sets of traffic lights, so the vehicles must change gears frequently. As anticipated, engine noise levels in power mode of the hybrid vehicle are a little higher than the corresponding engine noise levels in the other driving modes for the same vehicle as well as for the electric vehicle. As tyre noise is highly correlated with the vehicle speed, a slight noise increase is noted for power driving mode in comparison with the other driving modes of the hybrid vehicle.

For comparison, Fig. 3 shows the level histogram of time history of all driving modes, for the engine and tyre-ground interaction noises of hybrid and electric vehicles, for the urban road. The time the cars spent in neutral gear varied in all courses (depending on whether the traffic lights were red or green). This has been included in the respective histograms. The histogram of power mode is slightly displaced towards higher levels (hybrid vehicle). As compared with the same histograms for the suburban road, Fig. 2, the differences between power mode and the average of the other driving modes is less for the urban road.

Table 2 summarizes the overall $L_{eq}$, for engine and tyre-road interaction noises, for each driving mode of the electric vehicle, along the suburban and urban roads. On normal driving mode along the suburban road, the engine produced, on average, 1–2 dB more noise, while the tyre noise was roughly the same on both roads.

The systematic measurements carried out in this study, under realistic driving conditions, with alternative fuel (hybrid and electric) medium size vehicles, in urban and suburban roads, have demonstrated that it is possible to quantify and analyse noise levels, using both the global equivalent level and the level histogram. With regards to engine noise, the hybrid vehicle was noisier than the electric car, roughly by 3 dBA, in suburban scenarios, and by 7 dBA, in urban roads. In the case of tyre-road interaction, the level of noise was roughly the same for both vehicles. Compar-

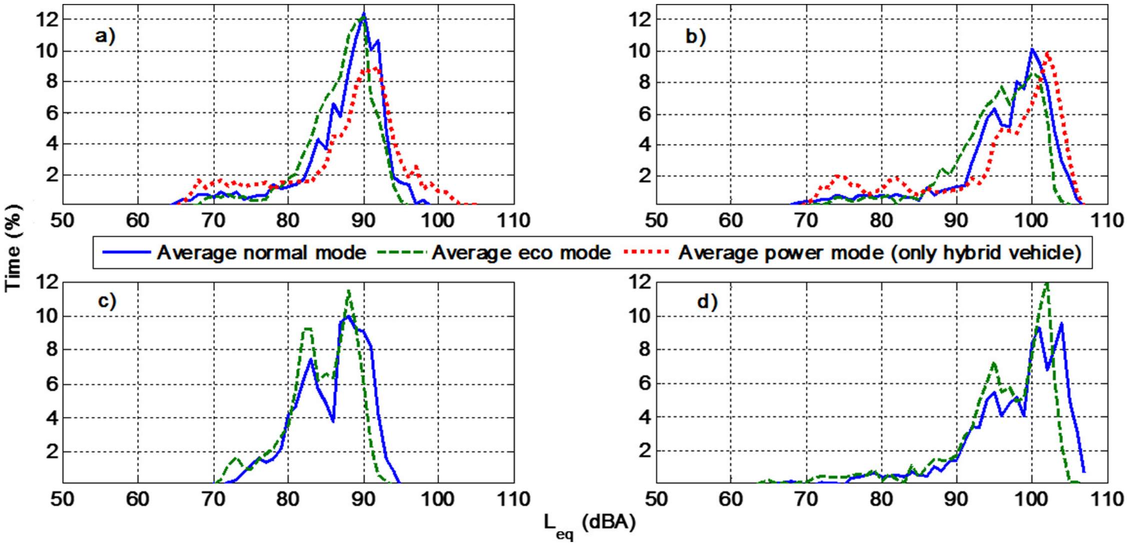

**Fig. 2.** Noise level histograms of the averaged driving modes for (a) engine hybrid, (b) tyre hybrid, (c) engine electric and (d) tyre electric $L_{eq,1s}$ along the suburban road.

**Table 1**
Equivalent engine and tyre-ground interaction noise levels (dBA) of the suburban and urban roads, for all courses for the hybrid vehicle.

| Mode | Suburban road | | | | Urban road | | | |
|---|---|---|---|---|---|---|---|---|
| | Engine noise (dBA ± 2 dBA) | | Tyre-ground interaction noise (dBA ± 2 dBA) | | Engine noise (dBA ± 2 dBA) | | Tyre-ground interaction noise (dBA ± 2 dBA) | |
| Normal | 90.8 | $\langle L_{Aeq}\rangle_{1-5}$ | 100.0 | $\langle L_{Aeq}\rangle_{1-5}$ | 84.7 | $\langle L_{Aeq}\rangle_{1-5}$ | 91.4 | $\langle L_{Aeq}\rangle_{1-5}$ |
| | 90.4 | 90.1 | 99.2 | 99.5 | 83.4 | 84.1 | 88.7 | 90.3 |
| | 89.2 | | 96.4 | | 85.7 | | 88.4 | |
| | 91.0 | | 101.8 | | 83.1 | | 91.4 | |
| | 88.7 | | 98.6 | | 82.8 | | 90.5 | |
| Eco | 90.1 | $\langle L_{Aeq}\rangle_{1-5}$ | 98.5 | $\langle L_{Aeq}\rangle_{1-5}$ | 85 | $\langle L_{Aeq}\rangle_{1-5}$ | 89.6 | $\langle L_{Aeq}\rangle_{1-5}$ |
| | 89.6 | 89.0 | 96.2 | 98.0 | 83.0 | 82.9 | 86.5 | 88.6 |
| | 87.8 | | 98.9 | | 82.8 | | 90.3 | |
| | 88.8 | | 98.8 | | 81 | | 88.4 | |
| | 88.1 | | 97 | | 81.3 | | 87.3 | |
| Power | 93.1 | $\langle L_{Aeq}\rangle_{1-5}$ | 100.4 | $\langle L_{Aeq}\rangle_{1-5}$ | 87.5 | $\langle L_{Aeq}\rangle_{1-5}$ | 91.6 | $\langle L_{Aeq}\rangle_{1-5}$ |
| | 92.3 | 92.3 | 98.3 | 100.2 | 87.3 | 86.7 | 90.8 | 90.9 |
| | 91.5 | | 100.2 | | 86.7 | | 92.3 | |
| | 92.4 | | 101.9 | | 85.3 | | 89.5 | |
| | 92.3 | | 99.3 | | 86.1 | | 89.7 | |
| Total | 90.7 | | 99.3 | | 84.9 | | 90.0 | |

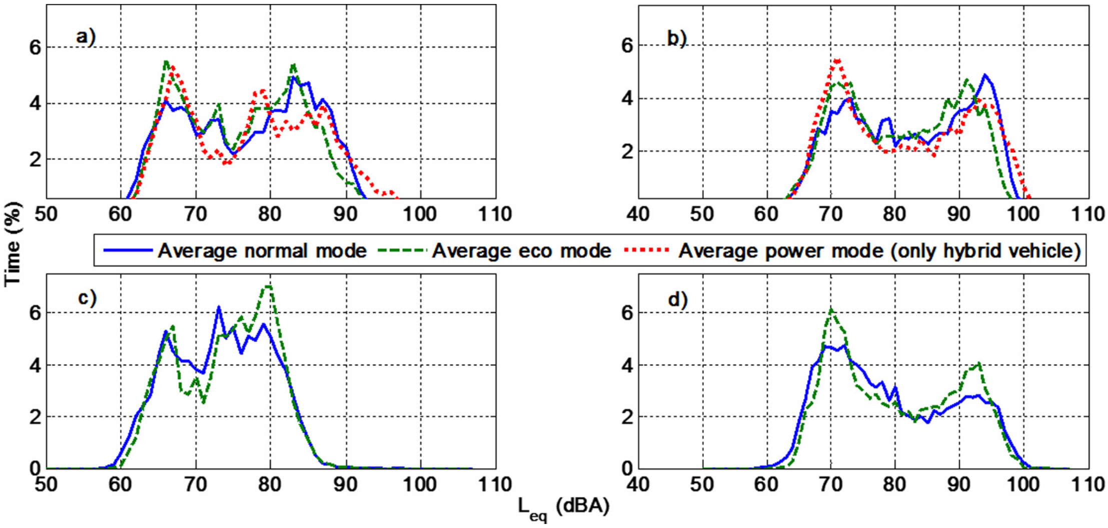

**Fig. 3.** Noise level histograms of the averaged driving modes for (a) engine hybrid, (b) tyre hybrid, (c) engine electric and (d) tyre electric $L_{eq,1s}$ along the urban road.

**Table 2**
Equivalent engine and tyre-ground interaction noise levels (dBA) of the suburban and urban roads, for all courses for the Electric vehicle.

| Mode | Suburban road | | | | Urban road | | | |
|---|---|---|---|---|---|---|---|---|
| | Engine noise (dBA ± 2 dBA) | | Tyre-ground interaction noise (dBA ± 2 dBA) | | Engine noise (dBA ± 2 dBA) | | Tyre-ground interaction noise (dBA ± 2 dBA) | |
| Normal | 87.7 | $\langle L_{Aeq}\rangle_{1-5}$ | 100.7 | $\langle L_{Aeq}\rangle_{1-5}$ | 78.6 | $\langle L_{Aeq}\rangle_{1-5}$ | 89.3 | $\langle L_{Aeq}\rangle_{1-5}$ |
| | 88.1 | 88.2 | 101.2 | 100.9 | 77.9 | 77.9 | 88.4 | 88.8 |
| | 89.7 | | 101.4 | | 77.4 | | 88.4 | |
| | 87.0 | | 100.2 | | 77.5 | | 89.2 | |
| Eco | 87.0 | $\langle L_{Aeq}\rangle_{1-5}$ | 99.4 | $\langle L_{Aeq}\rangle_{1-5}$ | 78.1 | $\langle L_{Aeq}\rangle_{1-5}$ | 89.0 | $\langle L_{Aeq}\rangle_{1-5}$ |
| | 86.3 | 86.6 | 99.2 | 99.4 | 78.2 | 78.2 | 88.9 | 88.8 |
| | 86.2 | | 98.9 | | 78.5 | | 88.8 | |
| | 86.9 | | 99.9 | | 77.8 | | 88.3 | |
| Total | 87.5 | | 100.2 | | 78.1 | | 88.8 | |

ing between both roads, the overall engine noise was, on average, 6–9 dBA higher in the suburban roads than in the urban roads for both vehicles, while the overall tyre noise was on average 9–11 dBA higher in the urban roads than in the suburban roads for both vehicles.

## 5. Noise levels estimation in the far field

In order to find out the noise level in the far field (which depends of the distance between the vehicle and the facades of buildings), we used the model implemented by Ibarra et al. [12,14], extrapolating the sound pressure level generated by the engine and the tyre-road interaction noises to the far field at 7.5 m and 1.2 m height, also corresponding with the ISO 11819-4 standard [22].

The extrapolation filter includes the attenuation of the engine noise through the engine hood [23]. The SPL (Sound Pressure Level) difference was evaluated experimentally using a speaker and two microphones, one inside and the other outside the engine hood [24]. The noise level, generated 1 m outside the hood, and reaching the microphone inside the hood was 27–28 dB, for both vehicles. Fig. 4 displays the average spectral distribution of the noise reduction by the engine hood at 1 m. As can be seen, this level difference is a little lower at low frequencies (20–500 Hz), due to the design and components of engine hoods.

Other filters were the attenuation due to spherical spreading and the attenuation due to ground interaction, which requires a propagation model. Here, we implemented the spherical wave model proposed by Attenborough et al. [25,26].

Thus, the ground attenuation can be calculated, provided there is an impedance model determined for the ground. In this study, a homogeneous locally reacting ground was assumed, with normalized acoustic impedance given by the Miki model [27,28].

Fig. 5 displays air absorption and the ground attenuation between the tyre microphone situated 0.2 m above the ground behind the vehicle, and the far field point, 7.5 m from the vehicle at a height of 1.2 m. Notice that the air absorption is irrelevant. The ground attenuation is significant in the full frequency range, with additive and subtractive effects depending on the ground impedance and source-microphones geometry set up. The Miramontes Avenue and Periferico ring road are laid with semi dense asphalt, with a flow resistivity of 9700, and 1200 $\mathrm{kN\ s\ m^{-4}}$ respectively. The soil impedance was measured according to geometry B of ANSI S1.18 Standard [29,30], at several points along the Miramontes and Periferico avenues, in order to obtain the average flow resistivity [31]. Fig. 6 shows the level difference curves of flow resistivity for the asphalt surface of Periferico Avenue.

Fig. 7 displays the average frequency spectrum of engine and tyre-ground interaction noises for hybrid and electric vehicles respectively. The engine noise emitted by the alternative fuel vehicles shows a frequency spectrum very different compared with that of petrol and diesel vehicles [32,33], due to some components at high frequencies (0.4–20 kHz). In the case of tyre-ground interaction noise, the spectrum is quite similar in both alternative and petrol/diesel vehicles, with a coincident pick at 1 kHz, as it is common in this kind of noise [34,35].

Fig. 8 shows the estimated levels and frequency spectrums at far field for both types of vehicle on both types of noise in 1/3 octave band, 20 Hz–16 kHz. With the propagation model we find

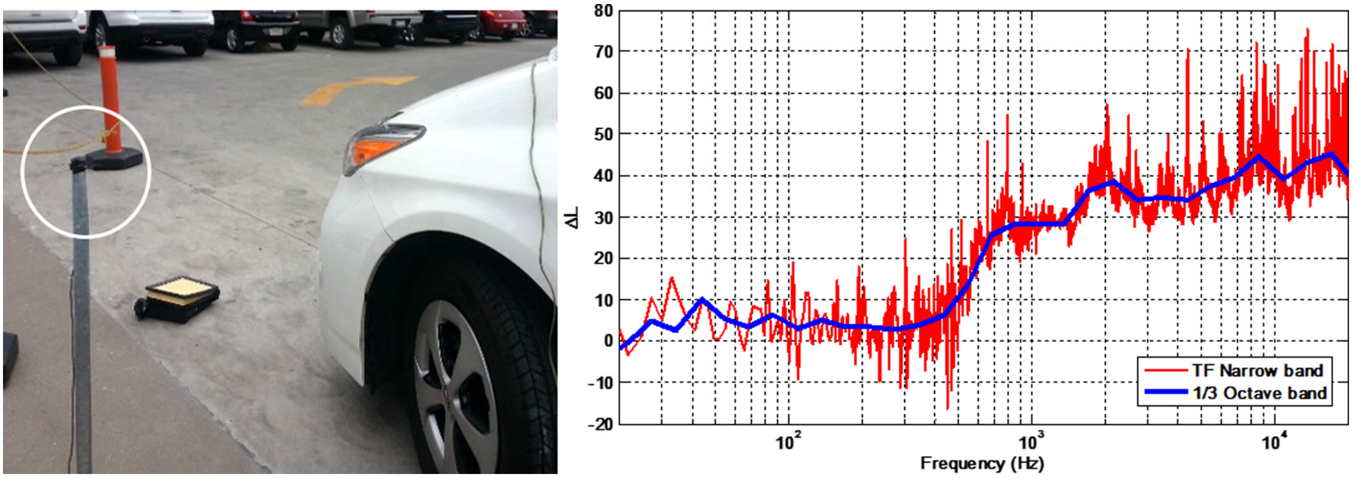

**Fig. 4.** Experimental set up of the Transmission Loss measurement (left), SPL difference between outside (1 m) and inside (engine) microphones.

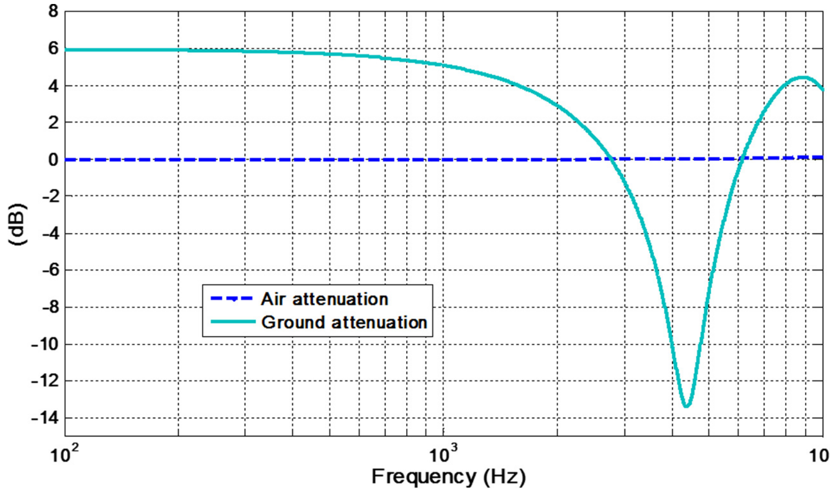

**Fig. 5.** The ground and air attenuation between the tyre microphone and far field point for a semi asphalt surface.

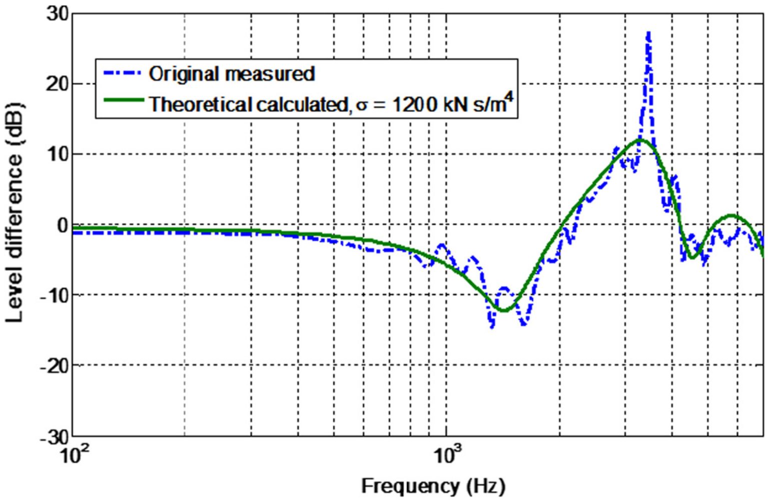

**Fig. 6.** Theoretical and experimental level difference curves of flow resistivity for the asphalt surface of Periferico Avenue.

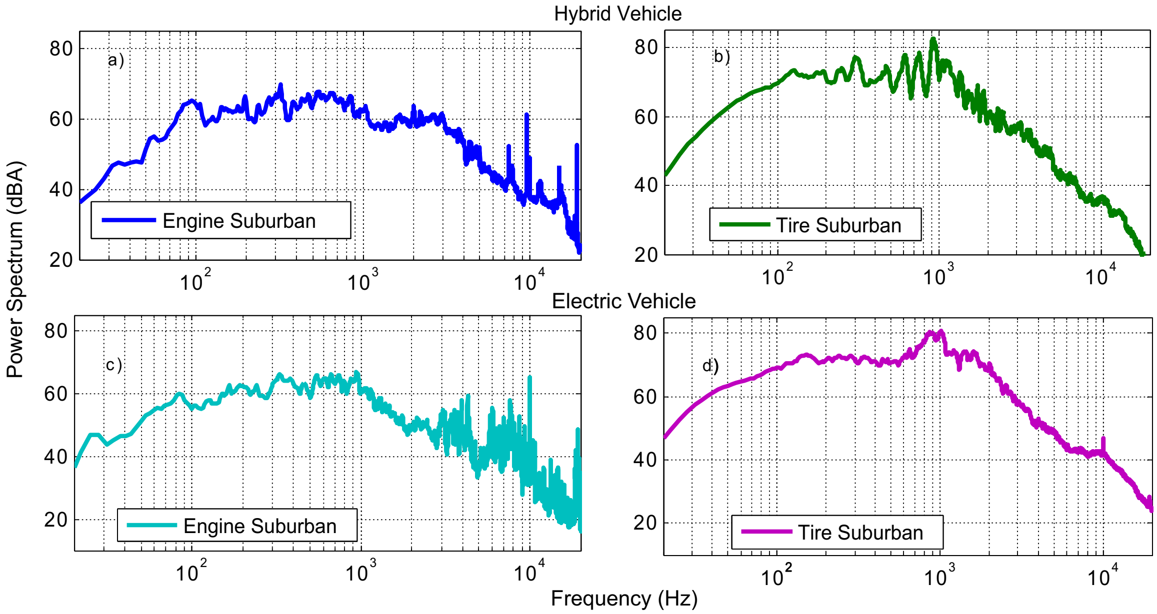

**Fig. 7.** Averaged frequency spectrum of engine and tyre-ground interaction noise for hybrid and electric vehicles.

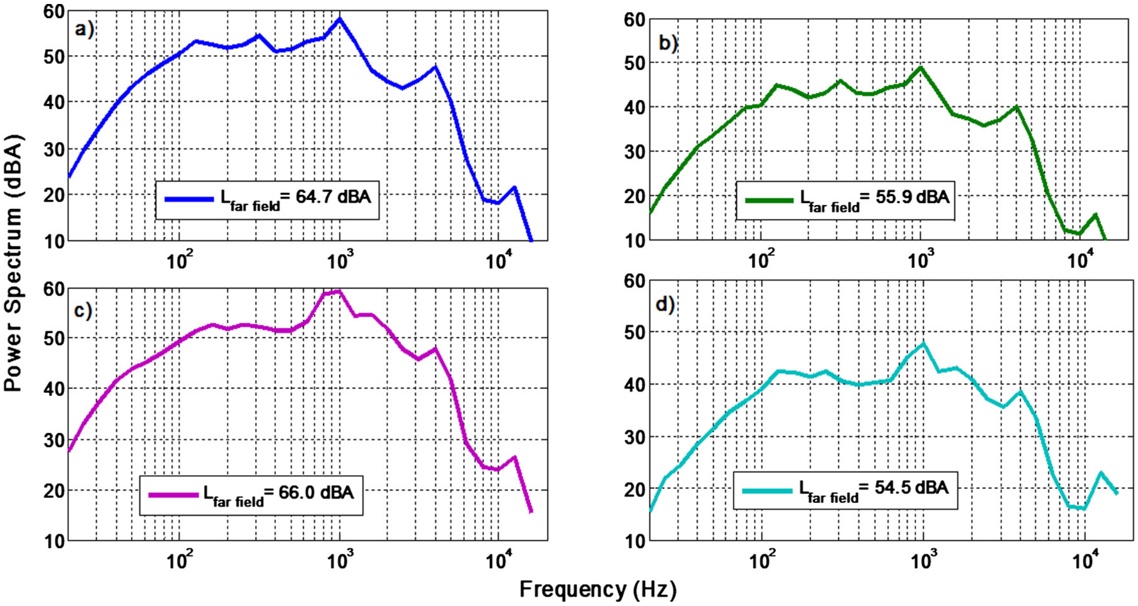

**Fig. 8.** Estimated level and frequency spectrum at far field for (a) hybrid vehicle in suburban, (b) hybrid vehicle in urban, (c) electric vehicle in suburban and (d) electric vehicle in urban roads.

the levels at far field (7.5 m), with an attenuation about 31–32 dBA in the case being analysed. An evident pick shows around 1 kHz in the extrapolated levels. This is due to the predominant noise of the tyre interaction with the ground, and is the noise remaining when the engine noise is attenuated.

## 6. Summary and conclusions

An on-board measurement system, able to characterize and compare driving modes of the alternative fuel vehicles, has been used in this work. The system measures the engine and tyre-ground interaction noises using two microphones, one located inside the engine hood and the other close to one of the wheels. Tests carried out under real driving conditions in suburban and urban roads in the south of Mexico City have demonstrated that it is possible to characterize, analyse and estimate the noise contribution of alternative fuel vehicles in near and far fields, using the global equivalent level, the level histogram and the propagation model to estimate the far field levels.

The hybrid vehicle is roughly 3 dBA, in suburban scenarios, and 7 dBA, in urban roads, noisier than the electric vehicle for the engine noise. In the case of the tyre-ground interaction, the noise is roughly the same for both vehicles. Comparing between both roads, the overall engine noise is on average 6–9 dBA noisier in the suburban roads than in the urban roads for both vehicles, and the overall interaction noise is on average 9–11 dBA higher in the urban than in the suburban roads for both vehicles. Using the propagation model we find the levels at far field (7.5 m), with an attenuation about 31–32 dBA in the case being analysed.

The results reported here, together with the methodological system, would provide a more accurate approach to traffic noise reports, in more representative environments, including considerations such as vehicle segment, engine type, vehicle age and road characteristics. It would also provide an instrument for a more reasonable administrative control of traffic noise, by the estimation and prediction of noise impact depending of the type of vehicle.

With these results, it can be concluded that alternative fuel vehicles have a notable impact on the engine noise in urban traffic, which could be beneficial for large cities; however, the benefit is lost in suburban roads because the tyre-ground interaction produces the predominant noise. This methodology and results are very useful for the implementation of noise mapping in big cities, simulating the impact of noise from vehicles with alternative fuels in urban roads.

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