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Influence of the automotive Start/Stop system on noise emission: Experimental study

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ABSTRACT

One of the most common environmental impacts of road transportation is the traffic noise. Linked to this, Start/Stop is a technology which has demonstrated to save fuel by powering off the engine when the vehicle is stopped, such as in front of a traffic light, and restarting the engine instantly when the driver pushes back the pedal brake to proceed. The technology helps also to reduce the CO_2 emission, playing a key role in a way to accomplish stringent emission norms for vehicle manufacturer. However, we are not sure whether it reduces the noise emission and how much? Thus, the main aim of this work is to assess the engine noise emissions of a vehicle incorporating a Start/Stop system in urban traffic, and compare it with those radiated by the mean traffic stream. Experimental results demonstrate that there are no contributions of the Start/Stop system to reduce meaningfully the engine noise in urban traffic.

The theoretical model is included to estimate the noise contribution in far field, as a part of a methodology of acoustics measurements for automotive vehicles.

1. Introduction

Reducing fuel consumption has become a priority for vehicle manufacturers, forced by the pressure of the worldwide authorities and environmental considerations, such as climate change [1]. A device which claims to reduce fuel consumption is the Start/Stop system (S/S in the following), which powers off the engine at stops as long as they accomplish certain conditions and re-start automatically when the driver needs to resume the trip. This automatic S/S system is increasingly common in American cars in recent years [1].

In an urban driving cycle, consisting of a route of 7 km and 12 stops of 15 s each, the S/S system reduced fuel consumption of a vehicle by up to 8% [2]. For example a diesel vehicle equipped with a S/S system running along two representative urban circuits (5.1 and 8.7 km) radiated to atmosphere a 20% less CO_2, in average, in comparison with a similar vehicle without the S/S system [3].

Therefore, whilst the S/S system gets a substantial reduction of fuel consumption and CO_2 emission, there are scarce published data that demonstrate whether it produces any beneficial effect on noise emission. Traffic noise is the most extensive cause of environmental health problems in the world. For instance, about 210 million of EU citizens, over 44% of the EU population, are regularly exposed to road traffic noise which is above the level considered as healthy by the World Health Organization (WHO) considers to pose a serious risk to health [4]. In urban environment, the number of people exposed to road noise is at least 5 times greater than all other sources (railways, airports, and industry) [5]. Reducing emission noise from vehicles is therefore a public health imperative. It is also far cheaper than the cost of in mission noise control techniques, such as noise barriers, insulation and quiet surfaces. The costs of these noise control techniques per person protected are, on average, between 8 and 120 times more expensive than those for making vehicles quieter [6].

Nowadays the vehicle fleet is increasingly growing in urban environment, so that a sustainable acoustic environment has turned out to be a key issue and a technological challenge [7]. Many efforts have been made by traffic managers and vehicle manufacturers to reduce the road traffic noise. Most developed countries have established noise limits which cannot be exceeded. At the same time, noise emission limits of individual vehicles have decreased by 8–11 dB in the last 35 years [8]. However, community surveys indicate that noise annoyance in urban environments has maintained more or less constant along the last years [7]. It is argued that the significant reduction of noise emission limits of individual cars has been neutralized by the increase of the vehicle fleet.

Thus, the aim of this work is to elucidate whether the S/S system has any beneficial effect in the reduction of vehicle noise

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Table 1
Vehicle specifications.

Body style	Compact Hatchback
Engine	Intercooled Turbo Premium Unleaded I-3
Size	1.5 L
Cylinders	3
Max power	136 HP @ 4500 rpm
Max torque	120 N m @ 1250 rpm
Transmission	6 SP automatic
Drive	FWD
Gear final ration	3.42
Fuel consumption city combined	4.5 L/100 km

emission. This is carried out by measuring the engine noise emitted by a vehicle with an S/S system in an urban circuit, and comparing it with the average engine noise radiated by the same vehicle driven by a set of 3 drivers along the same circuit with the S/S system switched off. Ibarra et al. [9] proposed an on-board measurement system able to quantify the contribution of single vehicles to the road traffic noise. This system was based on the assessment of the engine and rolling noises by two microphones located inside the engine hood and close to one of the wheels, respectively [10]. This measurement system will be used here to measure just the contribution of the S/S system to the overall engine noise emission of a vehicle in an urban circuit. An analytical far field extrapolation model will be use to estimate the contribution in this situation [11].

The equipment and measurement system, as well as the complete test procedure, are described in detail in Section 2. The results from the measurements are summarized in Section 3. The predictions of far filed noise are analyzed in Section 4. Finally, the main conclusions of this study are outlined in Section 5.

According to the report "Towards the road collapse" [12], the vehicle fleet has increased considerably in Mexico, and some estimates suggest that by 2030 the vehicle fleet in the country will be about 70,192,669 vehicles. Of these, private car will be the largest category. Furthermore, according to the Mexican Association of Industry Automotive (AMIA), Mexico belongs to the club 15 countries with sales of automobiles, 86% grouped together marketing world . The INEGI reports that in 2013 are recorded over 4 and a half million cars, only in Mexico City [13].

Also, the market ratio of diesel and gasoline engines in Mexico is 5% and 95%, respectively, so that it looks rational to choose a

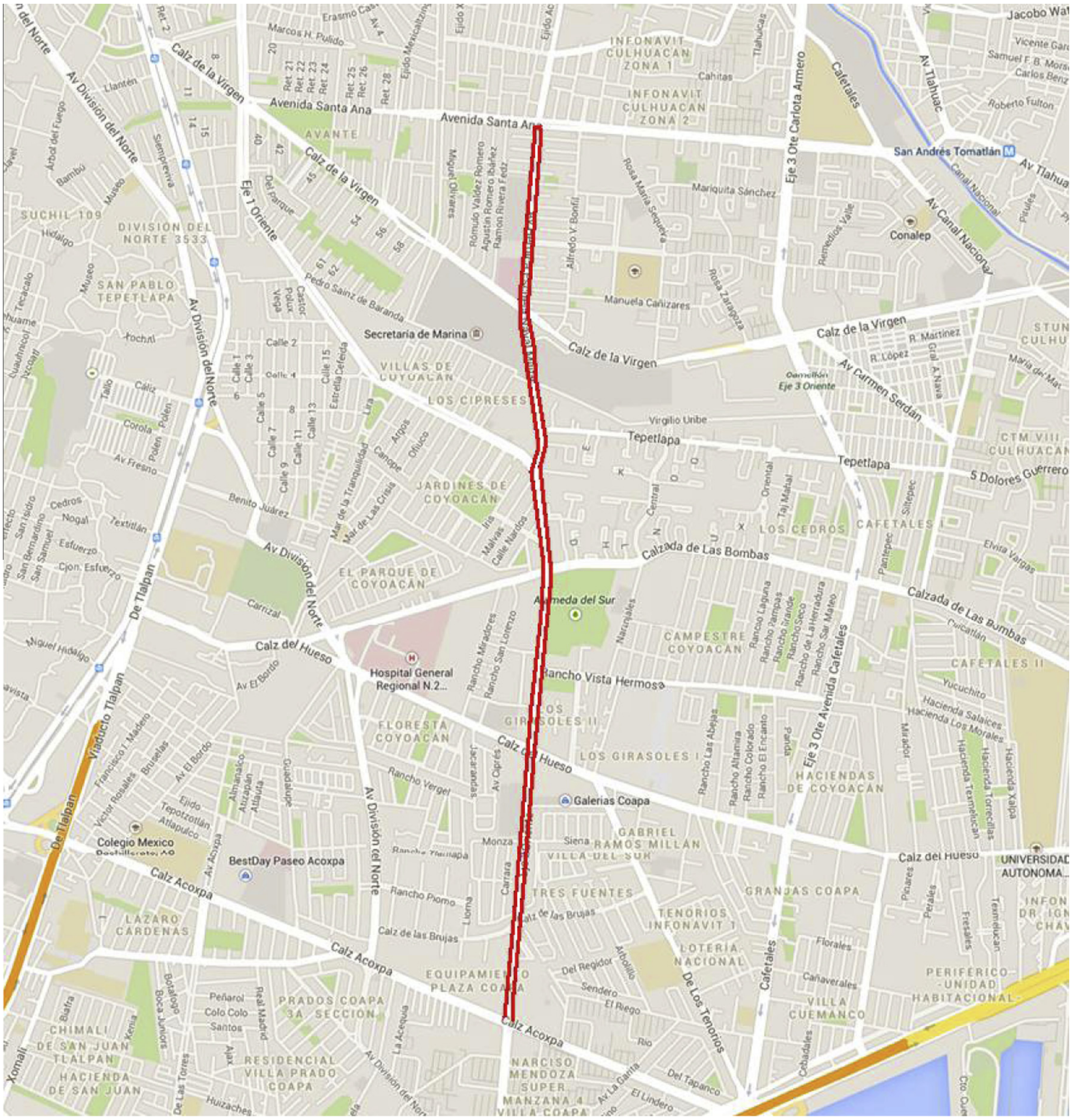

Fig. 1. Urban circuit map.

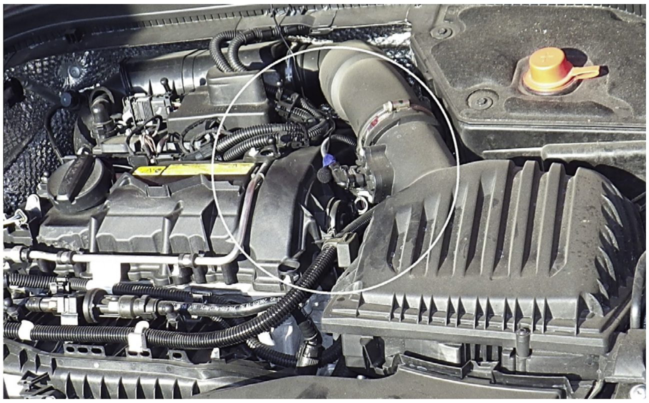

Fig. 2. Single location of the microphone for the engine noise.

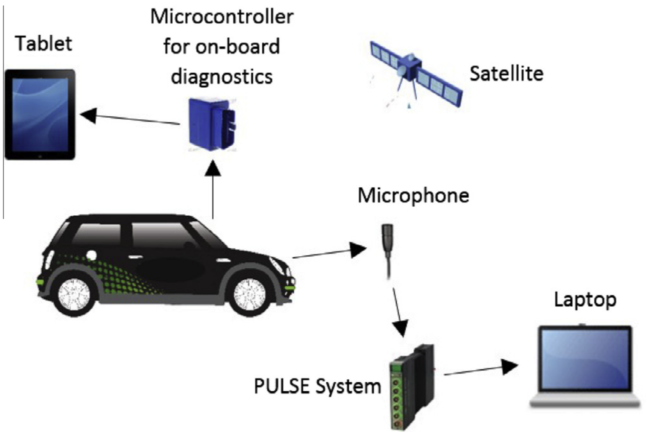

Fig. 3. Diagram of experimental data acquisition.

vehicle with a gasoline engine for the experiment. Therefore, a vehicle in the segment B, common in the large cities, was selected with S/S. This kind of vehicles are medium size, with high capacity and usually up to 100 kW (136 hp) power with middle fuel consumption.

Considering the statistics of car sales published by AMDA (Mexican association of automotive dealerships), the segment B is the most sold segment and a car with the S/S system of this was selected, and its specifications are summarized in Table 1.

The urban transport moves a huge load in the global mobility. For example, the distances travelled in urban areas in The EU are about 1800–3600 miles per year [14]. The principal route of drivers from their homes to the job place is between 8 and 12 km. Hence, an urban driving circuit of roughly 8.2 km was selected in Mexico City, since the travel time in Mexico City is between 30 and 45 min [15] Fig. 1. The urban course contains a street with speed limited to 60 km/h, with a traffic density of 40,000–80,000 vehicles per day, exposed to an equivalent noise level of L_{Ad} = 75–80 dBA. The circuit goes through streets of a three lanes per each direction of traffic. There is 24 traffic lights installed along the route.

2. Methodology

Three drivers were selected for running the same vehicle along the above described circuit, with driving license since more than 5 years. The three drivers completed three times the circuit with the S/S system switched on and off, in total 18 times.

Condenser electret microphone was used to measure the contribution of the engine noise in the near field. The maximum sound pressure level and dynamic range of the microphones, 135 dB and 110 dB respectively, are appropriate for the measurement of engine noise in real driving conditions. The microphone to record the engine noise in the near field was placed close to the air intake manifold, as it is the principal noise source with more contribution [16], Fig. 2.

The microphone was adjusted with the sound level meter, and was connected to a PULSE Labshop system to record the engine noise at the near field of the vehicle. Driving condition parameters were registered through the CAN BUS system of the vehicle, which contains an OBD2 module. This equipment is connected to the acquisition system through an ELM327 probe, recording information on the engine speed, the engine load and the acceleration. To reinforce the driving condition data, a GPS of ELM327 probe was utilized to register information on the vehicle location, vehicle speed, acceleration, distance and time, Fig. 3.

Driving conditions and noise were synchronously recorded with the vehicle running in real conditions, e.g. along the current traffic street in the urban course described above. Once the circuit is concluded, the recorded data are downloaded to a laptop for further post-processing and analysis.

3. Experimental results

Experiments were carried out with dry weather, along of February 2015, during morning (10–14) and evening (15–18) hours. Table 2 summarizes the parameters characterizing the average driving style of the three drivers. These parameters reflect the homogeneous traffic conditions and the similar driving styles. The traffic situation determines the time the vehicle was stopped and running (all courses were running roughly 40–50% of the time).

Table 2
Driving parameters along the urban course with the S/S vehicle.

Driving parameter		Driver					
		1		2		3	
		S/S on average	S/S off average	S/S on average	S/S off average	S/S on average	S/S off average
Vehicle speed	Average (km/h)	18.6	18.6	17.3	16.2	17.3	16.4
	Maximum (km/h)	56	58	60	60	58	58
Engine speed	Average (rpm)	993	1264	996	1238	948	1220
	Maximum (rpm)	2724	2568	2847	2895	2355	2714
Course	Distance (m)	8013	8173	8156	8150	8160	8200
	Running time (min)	16.8	16.3	16.9	17.3	17.1	18.0
	Stopped time (min)	8.5	8.8	10.7	10.5	9.5	9.9
km per liter	Average (km/l)	11.2	11.1	9.6	9.6	10.7	10.7
	Maximum (km/l)	64.4	62.0	69.8	69.4	71.9	69.3
Engine load	Average (%)	20.7	25.5	24.5	28.1	20.6	24.5
	Maximum (%)	160.3	145.4	189.7	186.3	110.1	156.2

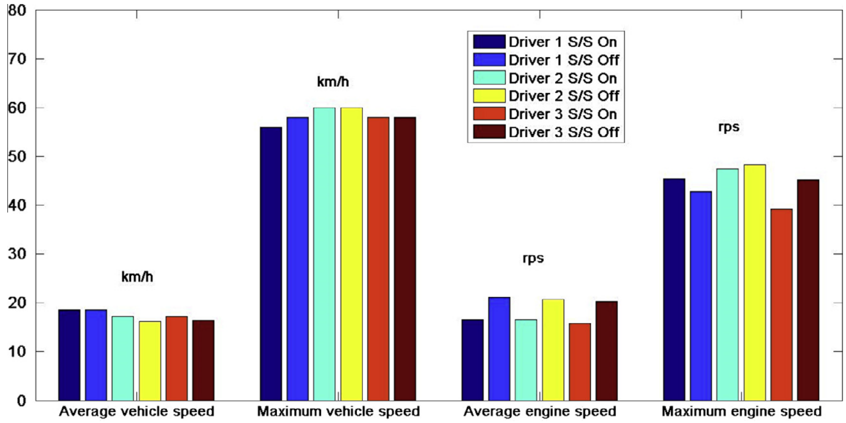

Fig. 4. Vehicle velocity (average and maximum) and engine speed (average and maximum) of every driver along the urban course.

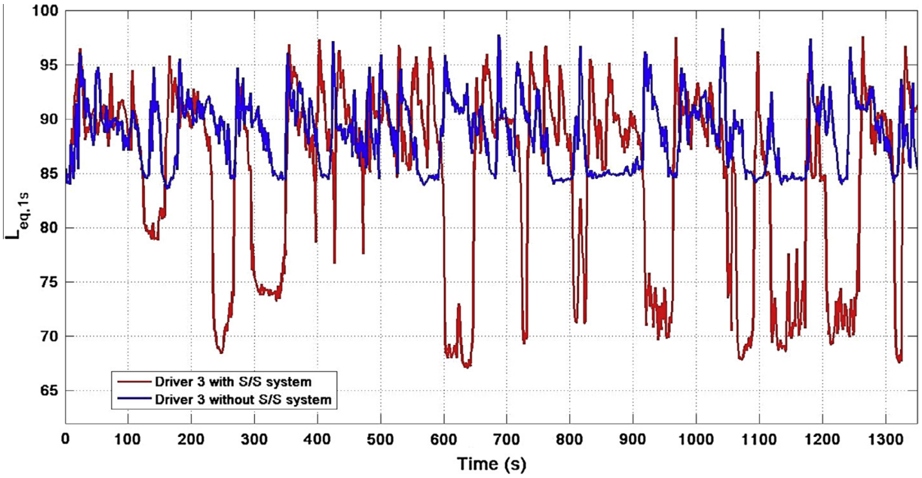

Fig. 5. Time evolution of the engine noise $L_{eq,1s}$ for the driver 3 with and without S/S system activated along the urban course.

The other parameters (vehicle speed, engine speed, and engine load), as expected, most of them are homogeneous, there is not necessary to have noise fluctuations because of these parameters as we can see in Table 2 and Fig. 4, nobody exceeds the maximum speed (60 km/h). The average speed in revolutions per second (rps) that were between 15 and 21 rps. The engine is in minimum speed during a significant time percentage 36.1% (driver average with S/S system off). The driver average with the S/S system on spent 35.8% of the time stopped (and so, with the engine powered off).

The use of harsh acceleration and deceleration is known to have a significant effect on engine noise [17,18]. Fig. 4 compares the average and maximum vehicle velocity and engine speed, in revolutions per second (rps), of every driving course. As we can appreciate none of the driver exceed 49 rps (2940 rpm) and there is not harsh acceleration that can influence in the overall equivalent noise.

As we mentioned in the previous section, the microphones were adjusted with a sound level meter, due to its specifications, the resultant sound levels of the experiments have a measurement uncertainty of ±2 dBA. Fig. 5 shows the time evolution of the $L_{Aeq,1s}$ of the engine noise of driver 3 with and without S/S system activated along the urban course. The circuit contains a lot of traffic lights, so that the vehicles must change speed frequently, staying more than one third of the time stopped (see Table 2). This render alternate high and low noise levels along the time histories. It is noticeable the minimum engine noise levels of driver 3 with S/S system on which result from powering off the engine when the vehicle is immobile. These minimum noise levels are significantly lower than the corresponding minimum noise levels of driver 3 with S/S system off.

Table 3 gives a summary of the overall equivalent levels throughout the whole urban circuit for each driver, for all course and for engine noise. It could be expected that the overall equivalent level L_{Aeq} of drivers 1–3 might be lower with the S/S system activated. However, the overall engine noise level for drivers 1–3 with S/S system on is only 0.4 dB lower than the average of the same drivers with S/S system off. The rather insignificant effect of powering off the engine during vehicle stops in the overall noise engine level is due to the preponderant weight of maximum noise levels in its calculation. Since

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

with $T = \sum Ti$, small values of $L_{Aeq,Ti}$ have a scarce effect in $\langle L_{Aeq}\rangle_T$ as compared with large values of $L_{Aeq,Ti}$. Fig. 6 displays the level histograms of the engine noises corresponding to the average of drivers 1–3 with and without S/S system activated, along the urban course. We can appreciate the averaged noise level of the drivers 1–3 with S/S system on in comparison with the average of the same drivers with S/S system off. Notice that both curves almost coincide above 86 dBA. The histogram of drivers 1–3 with S/S system on is displaced towards lower levels, as a consequence of turning off

Table 3
Comparison of overall equivalent levels, L_{Aeq}, along the urban circuit, for the three drivers.

Drivers	Completed courses (1–9)	Engine noise (dBA ± 2 dBA) with S/S system		Engine noise (dBA ± 2 dBA) without S/S system	
1	1	87.1	$\langle L_{Aeq}\rangle_{1-3}$	89.2	$\langle L_{Aeq}\rangle_{1-3}$
	2	87.0	87.4	87.7	88.3
	3	89.1		89.9	
2	4	87.9	$\langle L_{Aeq}\rangle_{4-6}$	87.8	$\langle L_{Aeq}\rangle_{4-6}$
	5	90.5	89.6	90.1	89.9
	6	89.9		90.1	
3	7	89.0	$\langle L_{Aeq}\rangle_{7-9}$	89.6	$\langle L_{Aeq}\rangle_{7-9}$
	8	89.4	89.5	89.5	89.7
	9	89.2		89.6	
Total	9 with S/S 9 without S/S	88.9		89.3	

the engine at the vehicle stops. Approximately 28.9% of the total time, the engine noise of average of drivers 1–3 with S/S system activated is among 57–81 dB, but really this is not significant to achieve a substantial reduction in the overall level.

If we analyzed the time signal in periods when the S/S system is on, in a stop (red light), the vehicle is with the engine off and suddenly the engine turns on, we can appreciate two impulse noises (<15 ms) almost 6 V and 8 V, shown in Fig. 7a, meanwhile the vehicle stays with engine idling maintains a continuous level 2.0–2.5 V. Analyzing the overall noise level of the whole frequency spectrum in those periods, we find that the level when the S/S system is activated (and so, restart the engine), is 5 dBA more than the level when the vehicle is with the engine idling during the stop, Fig. 7b. This Result is harmful, because the level of the vehicle with S/S system activated is equivalent to 3 vehicles with S/S system deactivated in that period of time.

4. Simulated noise levels in far field

In order to know the noise level in far field (which depends of the distance between the vehicle and the facades of the buildings), we used the model implemented by Ibarra et al. [11]. Extrapolating the sound pressure level generated in this case just by the engine noise to the far field at 7.5 m and 1.2 m height, then the level in far field will be

$$P_{T(7.5\mathrm{m})}(\omega) = H(\omega)\ P(\omega), \tag{2}$$

where $H(\omega)$ is the extrapolation filter between the engine microphone and the far field point, $P(\omega)$ is the sound pressure in the near field. The extrapolation filter $H(\omega)$ includes the attenuation of the sound through the engine hood [19]. The SPL difference was evaluated experimentally, with a speaker and two microphones, one inside the engine hood and the other outside the engine hood [19]. Then, the noise level at 1 m outside coming through to the engine hood will be $\Delta L_{1\mathrm{m}} = L_{engine} - L_{1\mathrm{m}} = 28$ dB. Fig. 8 illustrates the spectral distribution of this Noise reduction of the engine hood at 1 m. As it can be seen, this level difference is slightly lower at low frequencies (100–400 Hz), due to the design and components of engine hood. The noise level at 7.5 coming from the engine source will be

$$L_{T(7.5)} = L_{engine} - \Delta L_{1\mathrm{m}} - 20\ log\left(\frac{R_2 = 7.5\ \mathrm{m}}{R_1 = 1\ \mathrm{m}}\right) - \alpha_{air} - A_{ground} \tag{3}$$

where L_{engine} is the sound pressure level at the engine microphone, $\Delta L_{1\mathrm{m}}$ is the attenuation level due to the engine hood at 1 m, the third term represents a spherical spreading loss, α_{air} is the air absorption between engine source after engine hood and far field point at 7.5 m, and A_{ground} is the sound attenuation relative to the free field, due to the ground interaction effects between the engine noise after engine hood and far field point.

The calculation of the sound-ground effects requires a propagation model. Here, we will adopt the spherical wave model proposed by Attenborough et al. [20].

$$A_{ground} = \frac{e^{jk_0R_1}}{4\pi R_1} + Q\frac{e^{jk_0R_2}}{4\pi R_2} \tag{4}$$

where

$$Q = R_p(\theta) + [1 - R_p(\theta)]F(w) \tag{5}$$

is the spherical wave reflection coefficient on the ground. The contribution of the second term of Eq. (5) in Q for the total field in the receiver takes into account that the wave fronts are spherical, rather than plane (R_p). This contribution is also called ground wave, w is a complex variable called numerical distance [21], defined as

$$w = \frac{1+j}{2}\sqrt{kR_2}(\beta + cos\theta), \tag{6}$$

β is the normalized admittance of the ground, $F(w)$ is the boundary loss factor on the ground, whose expression is

$$F(w) = 1 + j\sqrt{\pi w}\ e^{-w^2} erfc(-jw), \tag{7}$$

erfc is the complementary error function. Note that w depends on the frequency through $k = 2\pi f/c_0$.

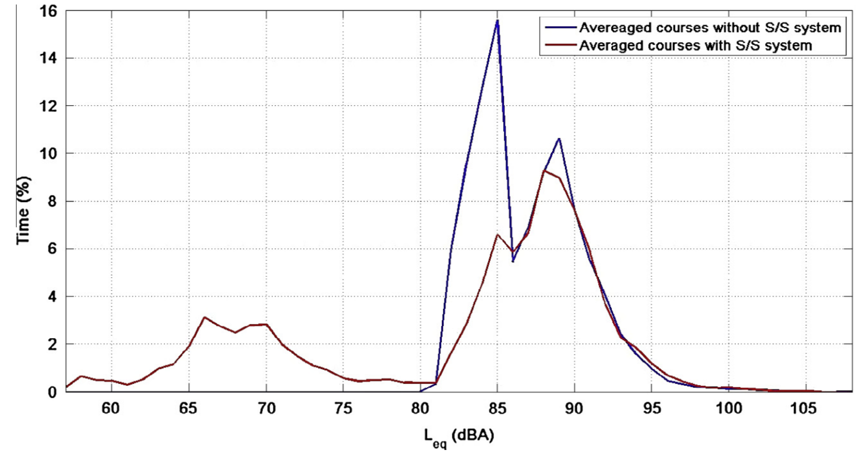

Fig. 6. Histogram of the averaged drivers 1–3 without S/S system (blue) and drivers 1–3 with S/S system (red) for the engine noise, $L_{Aeq,1s}$, along the urban course. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

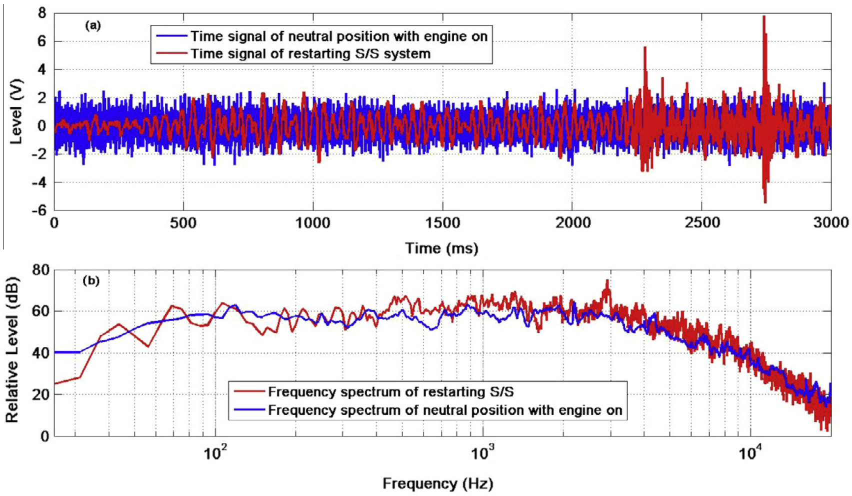

Fig. 7. Time signal (a) and frequency spectrum (b) of neutral position with engine on and restarting S/S system.

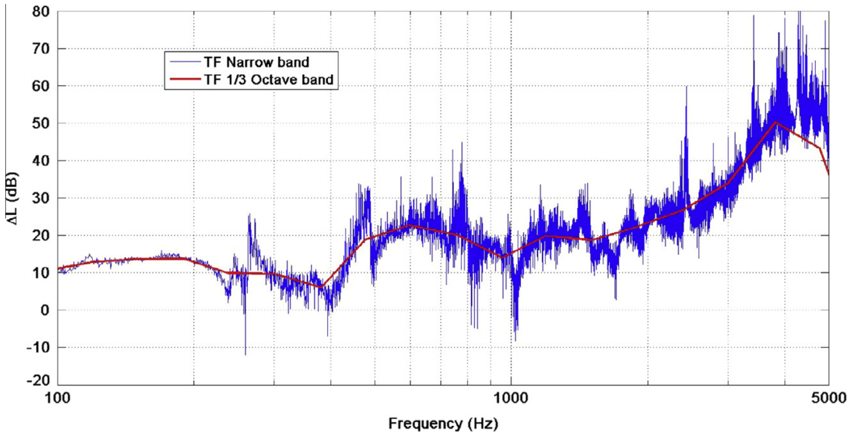

Fig. 8. SPL difference between outside (1 m) and inside (engine) microphones.

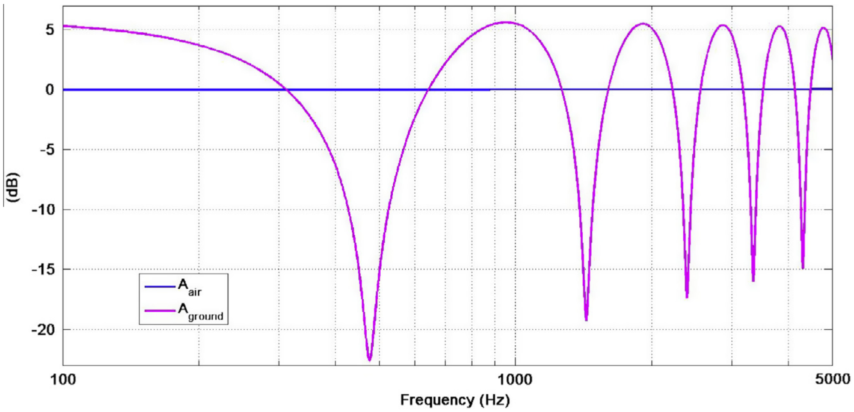

Fig. 9. The ground and air attenuation between the point outside of engine hood and far field point for a semi asphalt soil.

Thus, the ground attenuation, can be calculated provided that an impedance model, Z_s, is determined for the ground. In this work, a homogeneous locally reacting ground is supposed with normalized acoustic impedance given by the Delany–Bazley equation [22].

$$Z_s = \left(1 + 0.0571E^{-0.754} + j0.087E^{-0.732}\right) \tag{8}$$

where $E = \rho_0 f/\sigma$, ρ_0 is the air density, σ is the flow resistivity and f the frequency. Fig. 9 displays air absorption α_{air} and the sound attenuation A_{ground} between the point 1 m after engine hood, 1 m above the ground, and the far field point 7.5 m from the vehicle at a height of 1.2 m. Notice that the air absorption is insignificant. The ground attenuation is relevant in the whole frequency range, with additive and subtractive effects depending on the ground impedance and source-microphones geometry. The material of the Miramontes Avenue is semi dense asphalt with a flow resistivity of 9700 kN s m^{-4}, the soil impedance is measured according to geometry B of ANSI S1.18 standard[23], in several points

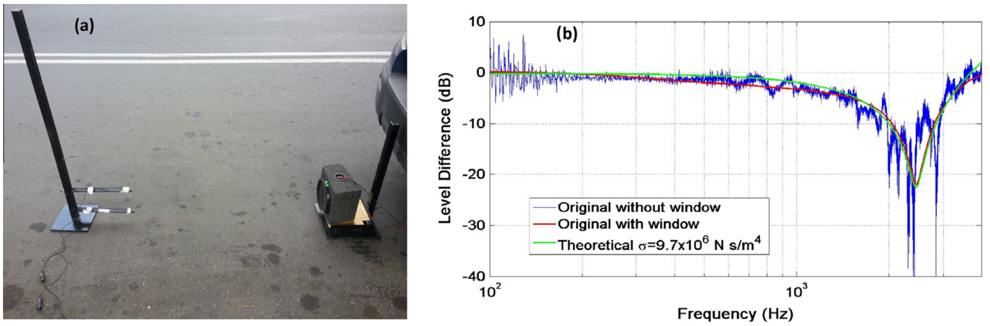

Fig. 10. Experimental setup (a), theoretical and experimental level difference curves of flow resistivity for the asphalt soil.

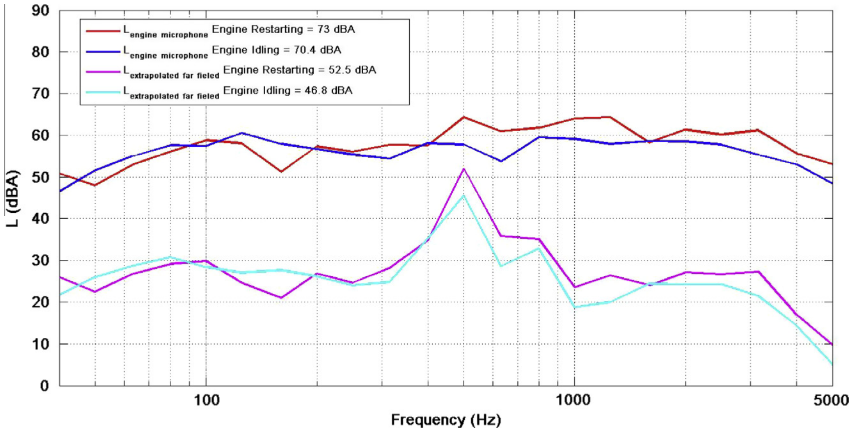

Fig. 11. 1/3 octave spectral levels of the engine noise and far field noises extrapolated by the vehicle with and without S/S system activated.

throughout Miramontes avenue, in order to obtain the averaged flow resistivity, Fig. 10 shows the experimental setup, and theoretical and experimental level difference curves for the asphalt soil.

Finally, in Fig. 11, we have the extrapolated levels from the engine noise in 1/3 octave band, 40 Hz–5 kHz. In this bandwidth we can appreciate a higher level when the S/S system restarts the engine as before (Fig. 7b), with the extrapolation model we find the levels at far field (7.5 m), with an attenuation about 20–23 dBA in the case being analyzed, it can be seen a pick around 500 Hz in extrapolated levels, this is due to the contribution of asphalt soil reflection. In simulated noise levels at far field in short periods (when the vehicle is stopped in a red traffic light), the vehicle with S/S system activated is around 5 dBA noisier than the vehicle with S/S system deactivated.

5. Conclusions

We have reported in this paper the results of the engine noise measurements of a gasoline vehicle, with the S–S system switched off and on, in a typical urban circuit of Mexico City. The same vehicle has been driven by three drivers, three times with the S/S system turned off, and three times with the S/S system turned on each driver. An on-board measurement system has been used to record the engine noise of the vehicle running in real traffic conditions. The recorded data has been post-processed to assess the time evolution of the instantaneous noise levels, the overall noise levels, frequency spectrum analyses, the levels histogram along the circuit and Far field extrapolation levels. Whilst powering off the engine during the vehicle stops reduces clearly the minimum engine noise levels, it has an insignificant effect on the overall engine noise levels throughout the whole urban circuit, but contrary, if we consider the impulse noises registered when the engine restarts, we find that the overall level is 5 dBA more than if the car had remained with engine idling, even in the extrapolation to the far field. Hypothetically, if we expand these results and in a red traffic light, there are 10 vehicles with S/S system activated and restart again in green light all of them at once would be an annoying impulsive noise that exceed the level recommended by WHO.

With these preliminary results, it can be concluded that the S/S system has a negligible effect on the engine noise in urban traffic, and it could not be beneficial impact for large cities. Also, this methodology and these results are very useful in implementation on noise mapping in big cities simulating the impact noise of these type of vehicles with S/S system in a traffic lights or a complete urban circuit.

Acknowledgments

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